EOS

EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

VOLUME 84 NUMBER 25

24 JUNE 2003

PAGES 233–240

New DEMs May Stimulate Significant Advancements in Remote Sensing of Soil Moisture

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From Napoleon's defeat at Waterloo to increasing corn yields in Kansas to greenhouse gas flux in the Arctic, the importance of soil moisture is endemic to world affairs and merits the considerable attention it receives from the scientific community. This importance can hardly be overstated, though it often goes unstated.

Soil moisture is one of the key variables in a variety of broad areas critical to the conduct of societies' economic and political affairs and their well-being; these include the health of agricultural crops, global climate dynamics, military trafficability planning, and hazards such as flooding and forest fires. Unfortunately, the in situ measurement of the spatial distribution of soil moisture on a watershed-scale is practically impossible. And despite decades of international effort, a satellite remote sensing technique that can reliably measure soil moisture with a spatial resolution of meters has not yet been identified or implemented. Due to the lack of suitable measurement techniques and, until recently, digital elevation models (DEMs), our ability to understand and predict soil moisture dynamics through modeling has largely remained crippled from birth [*Grayson and Bloschl*, 2001].

Fortuitously, recent advancements in techniques for making high-accuracy DEMs may act as the Rosetta Stone that makes possible the interpretation of soil moisture levels using space-borne Differential Interferometric SAR (DInSAR) and existing satellites. Our results show that several new DEMs may be sufficiently accurate to allow for the consistent C-band DInSAR measurement of soil moisture in a wide variety of terrain, at least in mid-latitudes: namely, the recently improved 1:24,000-scale DEM National Elevation Dataset (NED of the U.S. Geological Survey; http://seamless.usgs.gov; only available for lower 48 states); and the recent Shuttle Radar Topography Mission (SRTM; www.jpl.nasa.gov/srtm; only available ~ ±60° latitude).

The purpose of this article is to demonstrate that these new DEMs can improve our ability to remotely sense Earth surface processes using existing satellites, and suggest that acquisition of DEMs of this accuracy in regions in which they currently do not exist—namely, Alaska and the circum-polar Arctic—would be useful toward this end.

Intriguing Patterns of Phase Change

Example differential interferograms (DIGs) showing spatial variations of DInSAR phase at both cultivated and uncultivated terrain in Colorado are shown in Figure 1. We made these DIGs using a DEM created by Intermap Technologies' Star3i airborne single-pass X-band interferometry system (5-m posting and 3-m RMS vertical accuracy) and C-band ERS-2 satellite data; the results using SRTM and the 1:24,000-scale NED DEMs are virtually identical.

Spatial variations in SAR phase in Figure 1 are clearly correlated with many locations where one would expect to see changes in soil moisture, such as farm boundaries, watershed boundaries, and stream channels. For example, variations should be expected between farm fields due to the effects of subtle differences in slope, aspect, tillage, and cover crop on evaporation, as well as differences in irrigation. A body of literature, reviewed here, supports the case that these intriguing patterns of phase change were caused by a change in soil moisture, though accurately inverting phase for soil moisture has yet to be demonstrated.

The DIGs in Figure 1 are subsets of similar images that form a 10-month time series of ERS-2 data [*Nolan et al.*, 2003]. Without high-accuracy DEMs, it would not have been possible to create such a long time series with such subtle detail, as DEM accuracy plays a key role in both increasing the DInSAR signal-to-noise ratio and allowing for all possible satellite acquisitions to be used, as described below. Thus, it is possible that time series such as these are repeatable anywhere on Earth that a DEM of similar quality is available, limited only by the standard SAR constraints. (e.g., vegetative density, farm plowing, shadowing/layover, repeat-intervals).

Importance of DEMs in DInSAR

If soil moisture is actually detectable using DInSAR, how has the signal eluded the attention of the DInSAR community when so little else has?

The short answer is that it has not. The first published DIGs conclusively demonstrated that a soil moisture signal exists, and is measurable using L-band DinSAR, at least in flat, agricultural areas [*Gabriel et al.*, 1989]; yet, development of this application was never pursued further.

The longer answer likely lies in the signal-to-noise ratio. SAR interferometry (InSAR) has the ability to measure the actual elevation of the Earth's surface, but Differential InSAR has the ability to measure small changes in elevation of the Earth's surface once the actual elevations are accounted for. The difference between the two may be thought of in terms of an FM radio analogy (which should not be taken too far): think of InSAR as measuring both a long-wavelength carrier wave (topography) in meters and a short-wavelength signal (deformation) in millimeters that rides on top of that carrier. DInSAR is the removal of the topographic carrier wave, leaving only the deformation.

The clarity of this deformation signal is therefore dependent on the accuracy with which we eliminate the carrier; that is, errors in modeling the carrier wave will introduce residual noise into the deformation signal. This uncertainty in topography can introduce a noise floor above the soil moisture signal level, especially with shorter-wavelength sensors that have less signal strength. Since that first L-band study [*Gabriel et al.*, 1989], only shorter-wavelength C-band satellites have been available, and the influence of a soil moisture signal seems to have largely gone undetected.

Phase is the primary observable in both InSAR and DInSAR, and it is important to understand how it is used in both. Phase is essentially a measure of two-way path length, reported in modulo 2π radians; change in phase can be converted to change in path length by multiplying by $\lambda/2\pi$, where λ is the radar carrier wavelength (about 5 cm for C-band). Most of an InSAR phase signal arises from parallax viewing from two radar antenna locations (from two orbital passes in the repeat pass method), with locations typically separated by 0 to 1000 meters (the interferometric baseline). This parallax results in phase differences that correspond to surface topography,

similar to stereo pairs of air photos. Thus, InSAR is a powerful tool for making DEMs.

Surface deformations also contribute to path-length changes and hence contribute to InSAR phase, independent of the baseline. These two contributors, static topography and surface deformation, are separated using differential InSAR where two interferograms are subtracted from one another, one of which is a synthetic interferogram made from a DEM that contains only static topographic information (i.e., no deformation). Deformation due to earthquakes, surface subsidence due to well-pumping, volcanic inflation, and glacier motion are some well-known examples of DInSAR accomplishments to date.

When small baselines are used, the influence of topography is small and the quality of the DEM used for the synthetic interferogram is less important. Unfortunately, baselines vary over a wide range, meaning that many pairs of data go unused because baselines are too large. Traditionally, DEM errors have restricted results to the detection of signals on the order of a centimeter or more; but recent, more accurate DEMs can reduce topographic noise to the point where millimeter-scale change detection may be possible with substantially relaxed baseline requirements, increasing the number of useful pairs of acquisitions.

A mathematical description for the influence of elevation uncertainty on DInSAR accuracy can be found from basic SAR theory. Topographic phase is dependent on the baseline separation between the satellite's positions at the times of acquisition (Equation 1), whereas the signal phase (commonly called deformation phase) does not have this dependency (Equation 2) [*Massonnet and Feigl*, 1998].

$$\Phi_{topo} = (h*2k*Bn)/(R*\sin\alpha) \quad \text{(Equation 1)}$$

$$\Phi_{sig} = \delta*2k \quad \text{(Equation 2)}$$

where Φ_{topo} is topographic phase, h is topographic height in meters, k is the wavenumber, Bn is the normal baseline separation between satellites, R is sensor height above ground, α is the incidence angle, Φ_{sig} is signal phase, and δ is change in path length in meters. For the purposes here, we assume that k, Bn, R, and α are sufficiently well known to not introduce noticeable noise, leaving h as the primary uncertainty in Equation 1, and δ as the signal of interest. If we assume that a signal-to-noise ratio of 0 dB is the minimum required to ensure valid interpretations, then equating Φ_{topo} to Φ_{sig} yields an equation for δ versus h that can be parameterized by Bn. This is shown graphically in Figure 2. DInSAR measures the relative phase change between pixels; thus, the relative elevation accuracy between pixels is probably a better measure of accuracy than absolute vertical accuracy in this case. Unfortunately, this metric is more difficult to measure and is typically not listed in specifications; as relative accuracy between pixels is often better than absolute vertical accuracy, weaker signals are likely more detectable than Figure 2 suggests. For example, our research shows that this relative accuracy is less than 0.5 m for Star3i, which eliminates virtually any dependence on baseline for 1 mm signal detection.

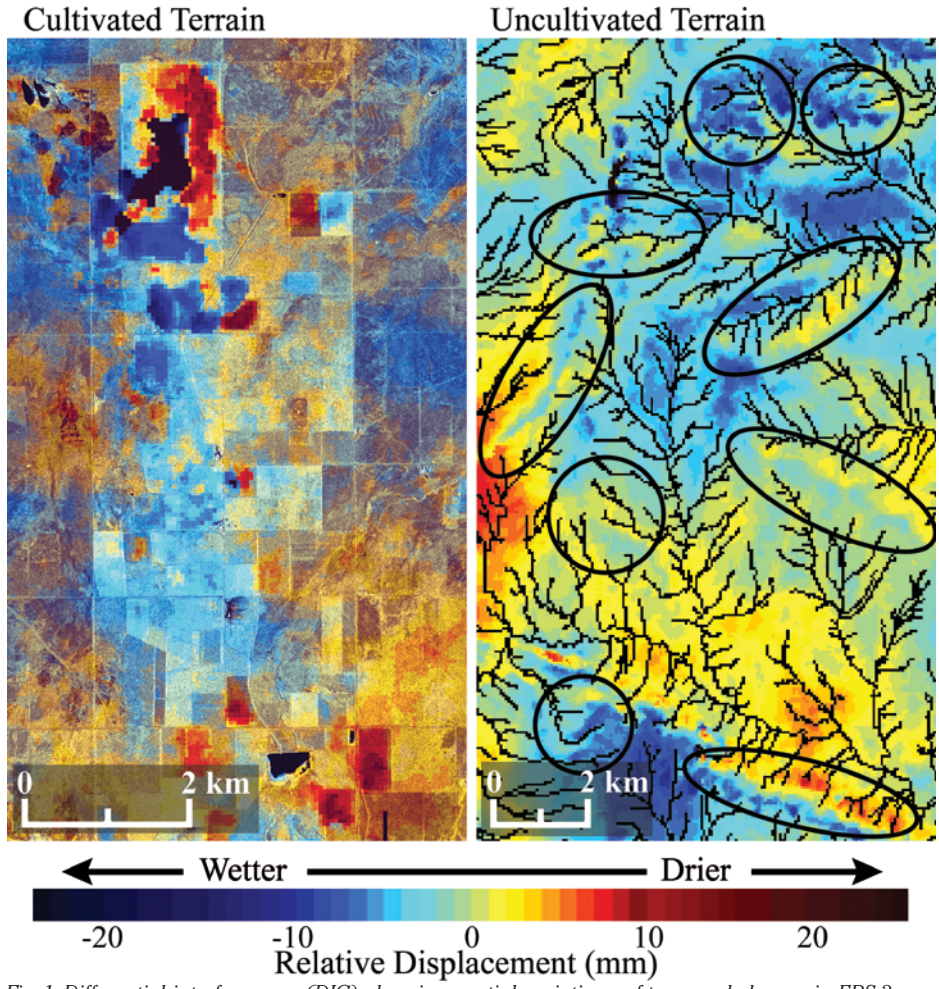

Fig. 1. Differential interferogram (DIG) showing spatial variations of temporal change in ERS-2 phase over cultivated (9 January to 13 February 2000) and uncultivated terrain (13 February to 19 March 2000) in southern Colorado, interpreted as variations in soil moisture caused by changes in penetration depth of the SAR microwaves. Black lines represent stream channels and are a good proxy indicator of topography; black circles and ellipses highlight locations where fine-scale changes in phase correspond with either farm field boundaries, ridges, or stream channels. The color bar indicates relative displacement within the scene, which is interpreted as a soil drying or wetting signal, as described in the article; Star3i backscatter was used to define color intensity in the cultivated region, accentuating farm field boundaries.

Given an InSAR baseline (0–1000 m) and assuming a low detectability threshold of 0 dB, we can determine the DEM accuracy required to be able to measure our signal reliably. Figure 2 shows required DEM accuracies for five typical baselines. Given a baseline of 250 m, for example, the detectable signal level gets smaller and smaller as the quality of the DEM improves from the USGS 1:250,000, to one created from ERS-2 data, to the three higher-quality DEMs at the far left (the accuracies used for these DEMs are described below). Given an uncertainty in topographic accuracy, Figure 2 can be used to determine the maximum allowable baseline required to measure particular signal amplitude. Such information may also be useful when determining whether a particular interferometric pair (separated by 24 or 35 days for Radarsat or ERS-2, respectively) is worth purchasing or analyzing, given a signal-strength of interest.

Subtle Signals and DInSAR

As DEM accuracy improves, therefore, several new DInSAR applications may now be within reach. While Earth deformation rates of several millimeters per year have been measured, typically these must be measured over time intervals long enough for the deformation to be a centimeter or more. These long time intervals increase the chances of temporal de-correlation, decrease the number of usable interferometric pairs, and eliminate the possibility of measuring intermediate fluctuations in deformation rates. This is particularly true in Alaska, the most tectonically active state, because the strong seasonal changes in surface dielectric (e.g., snow melt, rainfall, ground thawing) tend to dominant the phase signal when two or more months pass. Our ability to make DInSAR measurements of interseismic deformation, occurring at millimeters per year, may therefore be greatly facilitated by better DEMs. Another emerging DInSAR application is the measurement of soil moisture, and is treated in more depth here because of its familiarity to the authors.

Nolan et al. [2003] suggest that the most likely explanation for the phase variations such as those in Figure 1 are a change in soil

moisture. Here it was argued that all previously identified sources of phase variation (e.g., atmospheric anomalies, topographic residuals, vegetation, surface roughness, frost, dew) were insufficient to explain the patterns of phase in a 10-month time series of 8 ERS-2 DIGs covering cultivated and uncultivated terrain, particularly on the right-angle boundaries of flat farm lands. Much of this region does not contain soils susceptible to clay swelling, and changes in penetration were hypothesized to be the primary signal source.

The underlying theory behind the penetration depth source is that changes in soil moisture affect the soil permittivity and thus penetration depth, in a smoothly varying and quantifiable way, such that penetration depth decreases with wetter soils [*Nolan and Fatland*, 2003]. Unfortunately, the relationship between penetration depth and soil moisture is non-linear. For example, an increase in soil moisture from 10% to 15% VWC (volumetric water content) should yield a decrease in penetration depth of approximately 4 mm, but the same 5% change from 25% to 30% VWC should result in a decrease of less than 1 mm [*Nolan and Fatland*, 2003]. Whether due to clay swelling or penetration depth (which both affect phase in the same direction on the order of millimeters), however, it is now fairly clear that a soil moisture signal on the order of 1% VWC exists and is measurable with DInSAR on a 50-m spatial scale. Accurately inverting the DInSAR signal for soil moisture has yet to be demonstrated adequately due to a variety of obstacles [*Nolan et al.*, 2003].

To demonstrate the effect of DEM accuracy on the measurement of soil moisture, we repeated the same DIGs using different DEMs of the same study site (Figure 3). This study site was located in a high plains, rural area of south central Colorado. The geomorphology of this region is dominated by sedimentary mesa structures and hogbacks with tilted beds; and it is therefore to be expected that watershed divides are likely to separate soils with different properties that would influence soil moisture. The area is dominated by sparse grasses and shrubs, typically having less than 0.5 kg/m^2 above ground biomass, which is a rough C-band threshold for vegetative microwave interference [*Ulaby et al.*, 1996]. This arid region is also fairly flat and characterized by heavy rainfall events followed by hot, dry weather—a good location for both minimal topographic noise and maximal signal variation.

The first DEM we evaluated was one we produced from repeat-pass ERS data, but found that this DEM introduced atmospheric noise that was present in all subsequent DIGs in the form of several large, cloud-shaped anomalies (Figure 3a) as well as substantial random noise (speckle) even at 50-m postings. Large areas of de-correlation were present, correlated with the location of a steep canyon network trending northeast to southwest. Selection and processing of other pairs may have resulted in a DEM without such atmospheric anomalies and averaging of many such DEMs would likely have reduced the noise, but it was decided that any DEM made from repeat-pass interferometry should be avoided if possible both because of their noise problems and their poor vertical accuracy.

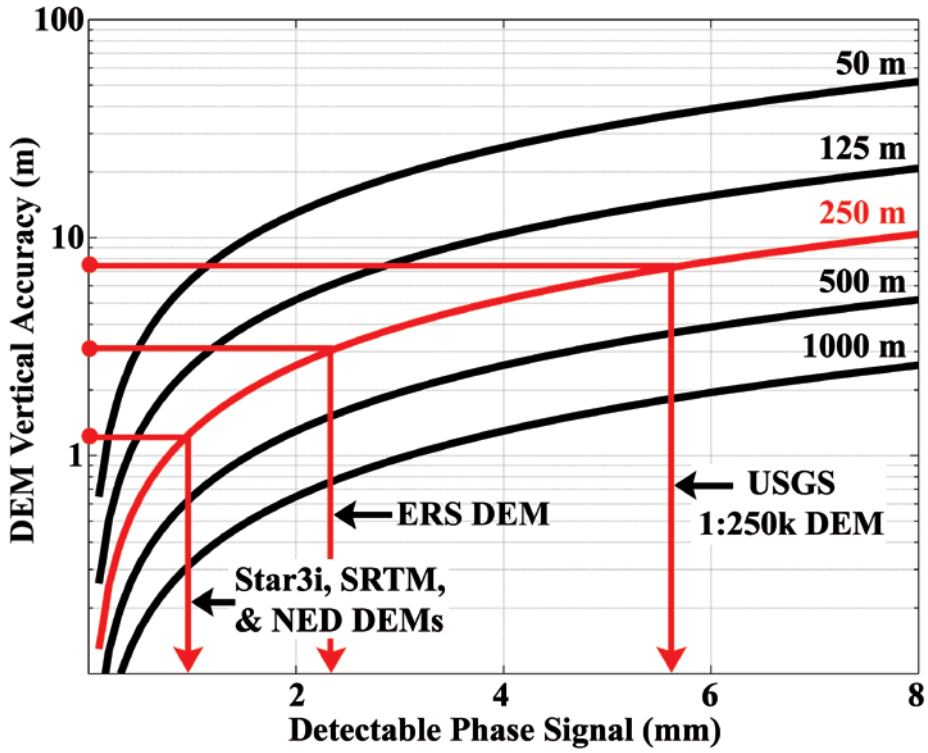

Fig. 2. Relationship between DEM vertical accuracy and phase-signal strength, parameterized by baseline. Because subtle soil moisture signals occur on the 1–mm level, an accurate DEM is required. Here, the RMS vertical accuracies from DEMs in Table 1 are plotted on the vertical axis. Decreased vertical accuracy limits the ability to detect subtle phase variations. For example, the March-April pair used in Figure 3 had a 250-m baseline. Because soil moisture variations are on the order of a few millimeters, only the better DEMs are able to detect the signal reliably. Better DEMs also increase the number of useful acquisitions because longer baselines can be used.

We next used a USGS DEM made from 1:250,000-scale maps, which are freely available for the entire U.S. (use of standard–pre-NED–1:24,000-scale DEMs requires many tiles to be joined). These DEMs were derived by the USGS from paper contour maps that were in turn derived from aerial photography. This DEM had large errors at the tile boundaries and a nominal vertical accuracy of 30 m. DIGs created with this DEM showed no qualitatively obvious relationship with hydrologic features (Figure 3b).

Next, we used a DEM made by Intermap Technologies' Star3i X-band airborne single-pass InSAR system, which has a nominal vertical accuracy of 3 m. The effect on the DIGs was dramatic (Figure 3c), with many phase change variations showing correspondence with hydrologic features (see also Figure 1).

Finally, we used two DEMs of intermediate accuracy: a 1:24,000-scale USGS NED DEM and an SRTM DEM (note that the SRTM DEM was a preliminary product and accuracy of the final product will likely be improved). Example DIGs made using these DEMs are not shown, because they are essentially identical to the Star3i DIG seen in Figure 3c. This second USGS DEM was not simply a mosaic of individual 1:24,000 tiles, but a rigorously merged product offered through the USGS' National Elevation Dataset (NED), in which the errors at seam boundaries have been corrected through interpolation or filtering; the uncorrected 1:24,000-scale mosaic had gross errors similar to the 1:250,000 DEM. The 1:24,000 NED DEMs are not available for Alaska.

All of these DEMs were compared to the Star3i DEM, which we consider to be the most accurate of the group. These results are shown in Table 1, and the RMS differences in elevation between these DEMs and the Star3i DEM were used to annotate Figure 2. The minimum signal strength predicted on Figure 2 clearly indicates why the Star3i, SRTM, and NED DEMs yield better results than the ERS or 1:250,000-scale USGS DEMs. Both the SRTM and NED elevations have less than 2-m RMS differences when compared to the Star3i DEM, substantially less than their nominal specifications, with somewhat higher errors when steep canyon terrain was included in the calculation.

The resulting DIGs were both offset by about 1.5 mm (agreeing well with theory) with RMS differences of 0.5 mm and the actual differences varying in spatial distribution. The SRTM DEM has a vertical resolution of 1 m, yet still yields results qualitatively similar to the Star3i DEM with 1 cm resolution. The most accurate DEMs (or at least those most similar to the Star3i DEM) show the strongest spatial correspondence with both large-scale (>1 km) and small-scale (~100 m) watershed features, as denoted by stream channels and annotations (see also Figure 1). The fine-scale structure of phase change is often visually correlated with the

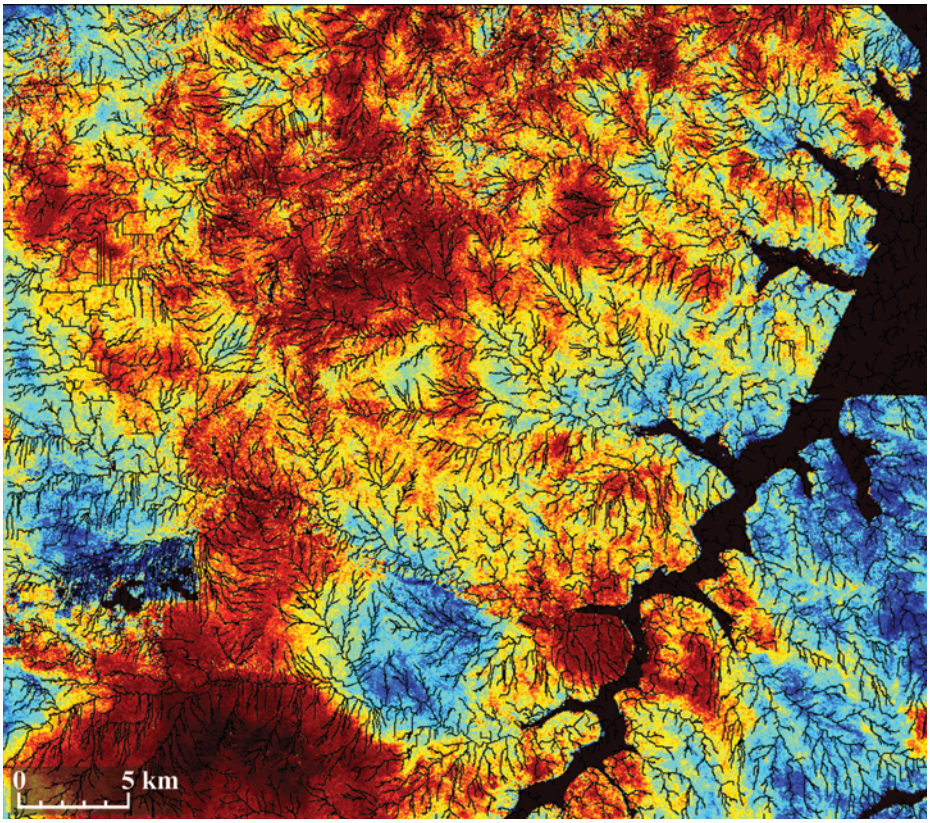

Fig. 3. The figures on this page are example DIGs made with DEMs of different vertical accuracy but same ERS-2 signal data. Color mapping is identical to Figure 1, though spatial scale has changed; large areas of black indicate decorrelation associated with a steep-sided canyon (which results largely from the synthetic interferogram). All DIGs used the 19 March – 23 April 2000 ERS-2 pair. (a) DIG made with an ERS-derived DEM.

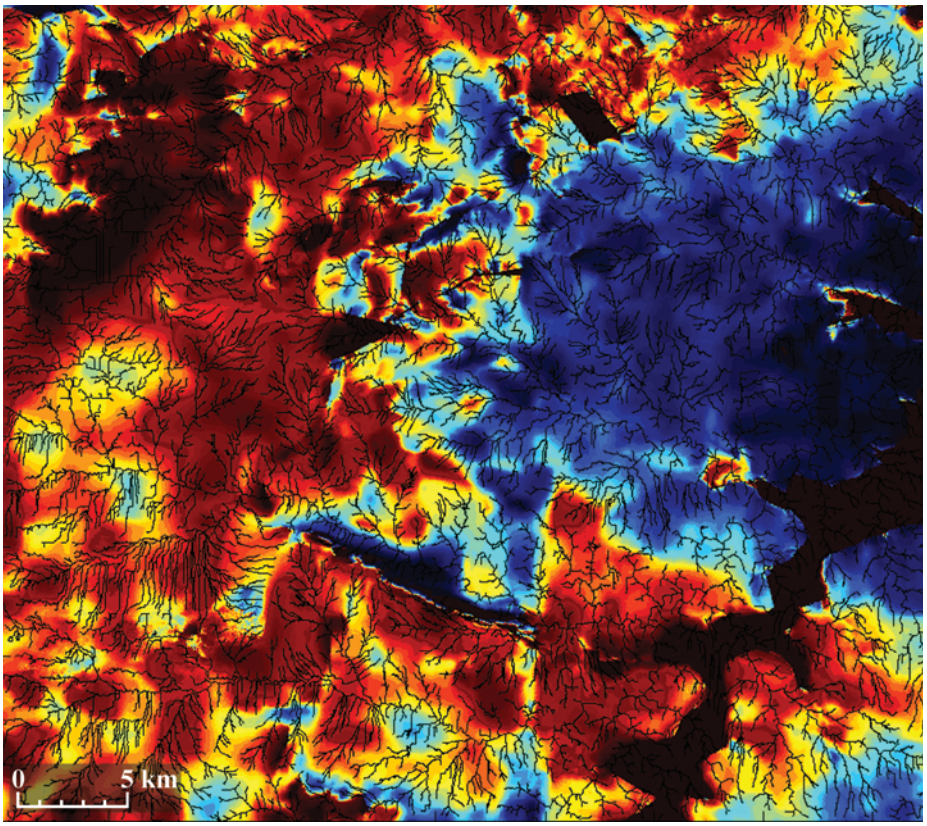

Fig. 3b. DIG made with a USGS DEM based on 1:250,000 scale map.

drainage network and farm field boundaries, eliminating atmospheric anomalies as the sole or even primary source of the variations.

Other DIGs within this time series [*Nolan et al.*, 2003] each reveal different patterns of phase change, yet each are still often visually correlated with surface hydrologic features, just as we would expect for a soil moisture source that varies temporally. Without use of a high-accuracy DEM, we may have been able to produce DIGs for the entire time series, but most of them would be useless for soil moisture analyses because noise related to topography (on the order of centimeters) would have overwhelmed the soil moisture signal (on the order of millimeters), as can be seen in Figures 3a and 3b. Thus, it is clear to us that high-accuracy DEMs can increase the value of remotely-sensed data without any changes to satellite technology or cost.

Future of DInSAR Measurement of Soil Moisture

Provided that further research can cross the divide between signal detection and accurate soil moisture quantification, it is possible that time series of DInSAR soil moisture measurement may be viable for many locations throughout the world, considering that the USGS NED DEMs are available for the contiguous 48 states, and that SRTM DEMs will soon be available for land masses between ~ ±60° latitude.

Unfortunately, there are no such publicly-available DEMs for most of Alaska and the circum-polar Arctic, where soil moisture plays the key role in global climate feedbacks. As far as we know, there is no topographic mapping mission planned for Alaska or the Arctic despite the obvious need, though several federal agencies are aware of the problem. Worse, current SAR satellite orbits limit observations to once per month. One solution is to make use of one of several existing airborne SAR systems, as they can both acquire new DEMs where they do not currently exist (using single pass methods) and acquire soil moisture information (using repeat-pass methods). While these repeat-pass systems are still in their infancy, advancements in GPS and inertial motion-compensation technology are rapidly making them more reliable with the added benefit of acquiring at nearly any temporal resolution. Putting them to work now in some of the many research watersheds throughout the country could well usher in a new era of hydrologic research and discovery.

Acknowledgments

This work was supported through the Arctic Regions Supercomputing Center at the University of Alaska-Fairbanks, Northrop Grumman Mission Systems, the Directorate of Environmental Compliance and Management at Fort Carson, Colorado, and the International Arctic Research Consortium.

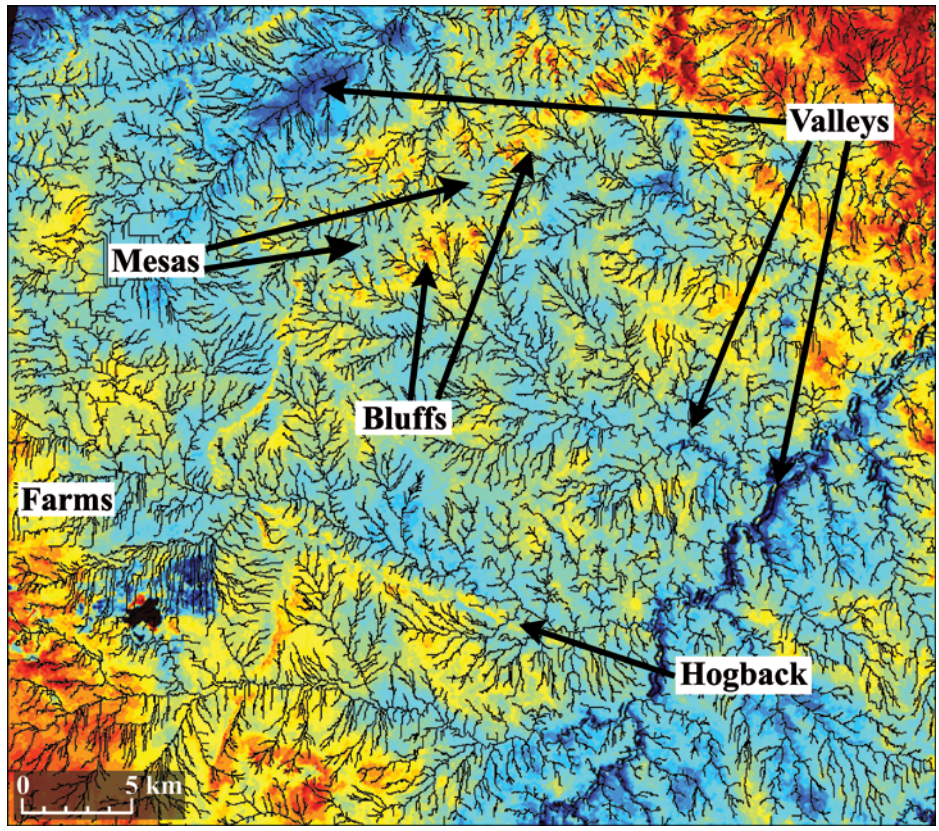

Fig. 3c. DIG made using Star 3i DEM. The quality of the DIG (in this case, how well phase change visually correlates with topography) corresponds with the quality of the DEM (Table 1) as theory suggests. For example, subtle features that correspond closely with topography can be seen in (c), but not in (a) or (b) (see also examples in Figure 1), even though the same signal data was used. Thus, the utility of SAR satellites (and others) can be greatly increased with no change to the satellites themselves.

Table 1. Comparison of Popular DEM Technologies

DEM	Vertical Accuracy			Vertical Resolution	Posting	Cost per sq km for typical user
	Nominal	RMS	Offset			
Star3i	3 m	N/A	N/A	1 cm	2.5 m to 10 m	$11 from archive or $36 - $72 new
USGS 1:250k	30 m	6.9 m	19 m	1 ft	2 x 3 arc seconds	Free
USGS NED 1:24k	15 m	1.2 m	0 m	1 ft	1 x 1 arc seconds	Free
SRTM	16 m	1.4 m	19 m	1 m	1 x 1 arc seconds	Free
ERS-2	—	3.1 m	70 m	1 cm	~ 25 m x ~ 25 m	Varies greatly
LIDAR	30 cm	Not tested	Not tested	1 cm	0.5 m to 5 m	$375 - $625

Note: RMS vertical accuracy was calculated as compared to the Star3i DEM, the most accurate DEM we had available, by first offsetting the DEM in such a way to minimize the RMS error. RMS error of the Star3i DEM itself is roughly 1.5 m, taken from independent comparisons to GPS reference points. SRTM offset (and possibly USGS 1:250,000) is likely due to the SRTM data being reference to an ellipsoid, not a geoid. ERS DEMs vary greatly in accuracy and cost, depending on many factors. We resampled all of these DEMs to 25 m posting for comparison. One arc second is roughly 30 m. Prices for commercial data (Star3i and LIDAR) vary, depending on accuracy, resolution, and value added by the vendor, and can be substantially higher than listed here. We did not test a LIDAR DEM, but included it here for comparison; specifications are typical for the industry. Aerial photogrammetry was not included explicitly in this table as the accuracies, resolutions, and prices span the full range shown here.

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Mine Flooding Complicates Option to Construct Underground Laboratory

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A decision by the Toronto-based Barrick Gold Corporation to turn off the flood pumps at its closed gold mine in Lead, South Dakota on 10 June complicates the potential use of the site as a deep underground laboratory for Earth science and physics studies.

Barrick shut off the pumps due to concerns about liability and mine safety, among other issues, even though the U.S. Congress has appropriated $10 million for the company to continue pumping for several years. The company currently is continuing its negotiations with the state of South Dakota to transfer ownership of the mine to the state. That transfer is an important step in the mine's eventual use as an underground laboratory.

An advisory panel to the National Science Foundation (NSF) stated in a 28 May report that Homestake, the deepest mine in the U.S., is "by far the most favorable site" for a deep underground science and engineering laboratory, based on geological suitability and relative costs. The panel, which considered three sites (see *Eos*, 1 October 2002, p. 446), said in its report that continued pumping of the 2440-meter-deep mine is important to maintaining mine stability and preserving the rock mass environment.

A number of scientists familiar with the issue said the incremental water seepage may not detrimentally affect many future Earth science and physics experiments at the mine, especially if it is possible for the pumps to be turned back on in the near future.

But they said the water seepage is not a positive step in efforts to have Barrick transfer the mine. They said the seepage could present safety and access problems as well as likely added time and expenses to prepare the mine as an underground laboratory.

In addition, there is strong concern that at least some important areas of study, including geomicrobiology, could be severely compromised at the mine because of the flooding.

William Roggenthen, professor of geology and geological engineering at the South Dakota School of Mines and Technology, said the Barrick decision "casts a pall" over the process of transforming the mine into a laboratory.

Homestake Still the Focus

The NSF panel noted on 28 May that any cost savings the mining company may realize by turning off the pumps "would not be worth the potential for destabilizing the flooded region and neutralizing this region with respect to microbial life study."

NSF spokesperson Curt Suplee said that, based on the panel report, the agency believes that it makes sense to focus on Homestake as the most favorable site, even after the pumps were turned off. Suplee noted that at this point NSF has no position about the pumping in the mine, because it is not yet available as an underground laboratory. He added that it is doubtful whether anybody knows how the flooding might affect microbial studies or cost increases in preparing the mine as a laboratory.

Uncertain Conditions

Brian McPherson, associate professor of hydrology at the New Mexico Institute of Mining and Technology, said it is very difficult to ascertain whether the flooding has harmed scientific opportunities.

"The most certain outcome of what is going on with the pumping being ceased is that now [the situation] is very uncertain, and we don't know what opportunities have been changed, reduced, or eliminated," he said. "It is going to take a separate study on its own to determine what these changes are, another layer of effort that probably won't be inexpensive ."

McPherson said that even with the pumps shut, some exciting geophysical, hydrological, and rock mechanics research there is possible. But he said the ability to conduct some studies will depend on hydrological diffusivity and permeability of the rock environment, which at this point are unknown.

Some of the first features likely affected by water are fracture zones—which typically have higher permeability than the surrounding rock environment—located close to the pumps. Fractures, McPherson said, are flow conduits where microbes could move, and where they may have been before the pumps were turned off.

The study of deep subsurface microbes that may feed on inorganic materials could be tied into research about the origin of life, and could be applied to the search for life on other planets, Tullis Onstott, professor of geosciences at Princeton University, has said.

McPherson noted that "geomicrobiology is the feather in the cap" for Earth science studies at an underground laboratory. "Hydrology is exciting to hydrologists and to the people in the arid Southwest," he mused, "but it doesn't hold a candle to answering questions about the origins of life."

Herbert Wang, professor of geophysics at the University of Wisconsin at Madison, concurred that seepage for 1 year or so would not present irreparable damages for rock mechanics or fluid flow studies. But he said that "the highest priority experiment from the Earth science perspective is the microbial life experiment: what type of bacteria survive with extreme temperature and pressure" at 2440 meters.

Barrick vice president Vince Borg said that the company intends to donate the mine site and facilities to the state of South Dakota for use as a laboratory. He said the NSF report's statement that Homestake is the best site "is a major step to clinch the deal" for transferring the site. He said the pumps likely would remain off until 2006, but that at a later point the mine could be de-watered quickly and the upper portion rehabilitated.

The Earth science community has collaborated with the physics community on an underground mine site, in part because the cost for two underground laboratories likely would be prohibitive. Wick Haxton, physics professor at the University of Washington and principal investigator for a proposal to the NSF to utilize Homestake as an underground mine, said that while he fought against Barrick's decision to flood the mine, he is trying to be pragmatic. "The decision is made. So we want to continue constructively, despite the flooding," he noted. "We are currently thinking through various ways we could adapt to a wet mine."

Roggenthen said that despite what may transpire with Homestake, one positive measure that has resulted from discussions about it and other sites is that "a portion of the geological community has been mobilized and came up with plans of what could be done with an underground mine."

—RANDY SHOWSTACK, Staff Writer