Potential hydrologic science contributions for an airborne SWOT simulator

[White Paper v3.0]
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An airborne SWOT simulator (e.g. KaSPAR, Moller and Carswell, 2009) has potential to make strong scientific contributions to a variety of outstanding problems in surface-water hydrology. This document provides a preliminary description of several such problems, and is intended to stimulate discussion of other ideas and potential targets as well.

Like SWOT itself, a key strength of an airborne imaging altimeter is its ability to acquire water and land surface elevations, with centimeter-scale precision, in swath-imaging mode. The latter is crucial because unlike a profiling instrument, it enables mapping of spatial heterogeneities in, say, water free-surface slope, or the variations in relative surface elevation among a collection of ponds. This represents an orders-of-magnitude increase in data density to a scientific discipline accustomed to either sparse point-based measurements or no measurements at all. Put simply, imaging altimetry promises a great leap forward for land surface-water hydrology in much the same way that satellite radar altimetry liberated physical oceanography from a limited collection of tide gauges (Smith and Pavelsky, 2009).

To illustrate the strong scientific value that airborne imaging altimetry would afford hydrologic science, consider the following six questions that KaSPAR could address:

1. How do flood waves actually propagate and dissipate downstream (as opposed to how we model it), especially in geomorphologically complex, “real-world” river systems? (potential field targets: Saskatchewan River; also Colorado River, Ohio River)

2. How important is the presence or absence of ground permafrost as a control on the volume and dynamics of surface water storage in northern areas? (potential field targets: Canadian Shield; also southwestern Alaska).

3. What controls the formation and drainage of meltwater ponds and rivers on top of the Greenland ice sheet; and how important are they to pressurizing the bed thus potentially accelerating glacial ice flow? (potential field target: western Greenland)

4. What can water surface elevations in lakes, ponds and rivers tell us about groundwater recharge, potentiometric surface gradients, and flow patterns in unconfined aquifers? (potential field targets: Nebraska Sand Hills, North Dakota prairie potholes)

5. To what extent will SWOT data reduce uncertainty in flood risk mapping for river management, insurance and re-insurance applications (potential field targets: Iowa and Cedar rivers).

6. Where will the next Mississippi River Delta avulsion happen? What parts of the delta are most vulnerable to subsidence, sediment starvation, and flood inundation? (potential field target: Mississippi River)
7. Can we remotely estimate evaporation losses from water impoundments? (potential field targets: Metropolitan Water District reservoirs, California; Cargill Salt Ponds, San Francisco)

Five of these (1 – 5) are developed in further detail next.

<u>How do flood waves propagate and dissipate downstream?</u>

A key task of hydrologic flood routing models is to predict the peak height and timing of a flood wave as it propagates downstream. Current models for doing this are have strong theoretical basis (e.g. solutions of the Navier-Stokes equations) but are data-poor. Frictional resistance of the bed must be parameterized, and models fare worst in areas of complex hydraulic geometry and branching channel flows. From a hydrological standpoint this restricts our fundamental understanding of how a flood wave interacts with complex floodplains, and how important adjacent wetlands may or may not be to absorbing it. From an ecological standpoint it limits how well we understand the recharge of water and sediment to riparian wetlands, as well as carbon sequestration and trace gas release from seasonally flooded areas.

An ideal natural laboratory to study this problem with an airborne SWOT simulator is the Saskatchewan River and surrounding Cumberland Marshes, Canada. In 1873 a river avulsion abruptly diverted the main-stem flow of the Saskatchewan River north, creating a complex network of anabranching river channels and crevasse splay sedimentary deposits (Smith et al., 1989, K.M. Farrell, 2001). The original channel, in contrast, maintained its single-thread form with reduced flow through the channel. In 1963, the E.B. Campbell hydroelectric dam and reservoir was built across the Saskatchewan River some 30 km upstream from the avulsion node. This dam now predictably releases ~1 m hydrologic pulses each day in response to the diurnal cycle for electricity demand. These mini-floods propagate down both the old and new channels of the Saskatchewan River simultaneously, offering a unique opportunity to directly measure how the same flood wave reacts to two very different channel geometries.

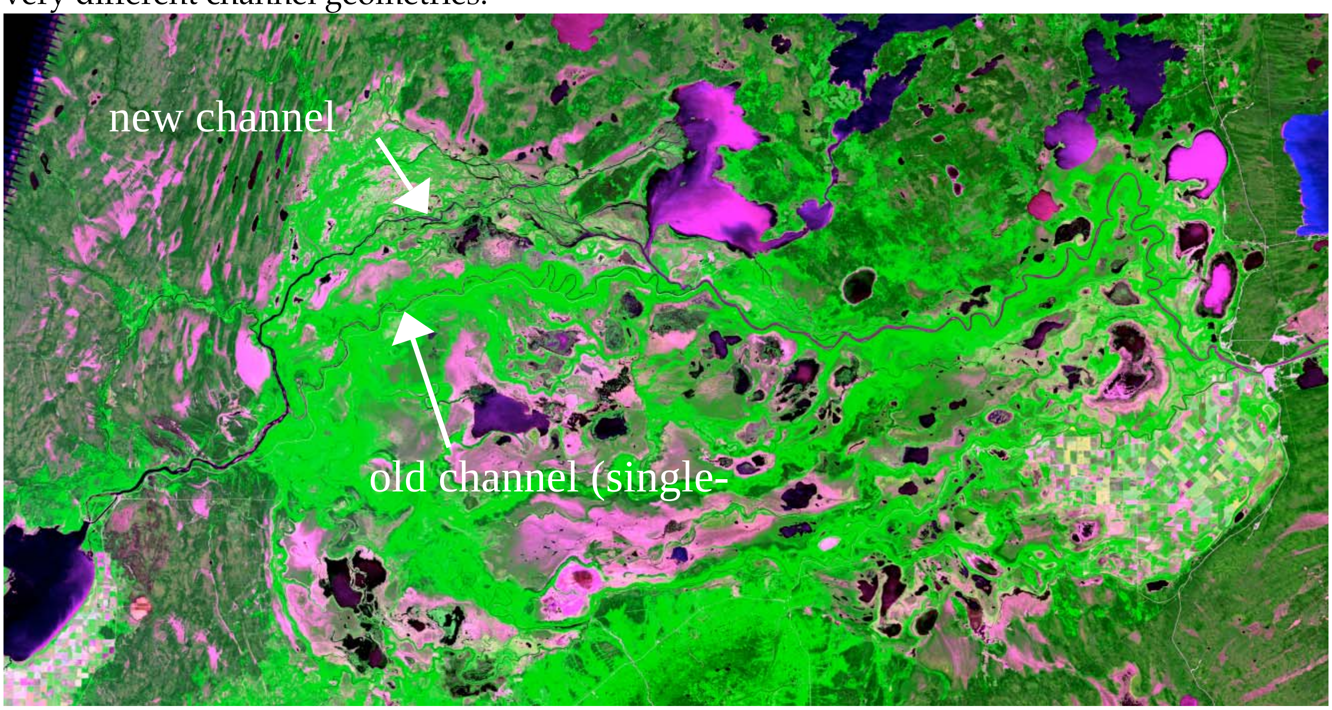

Fig. 1: The Saskatchewan River and Cumberland Marshes, Canada. A major avulsion in 1873 created a second, anastomosing river channel with much greater hydraulic complexity than the first. A hydropower dam at left sends mini-floods (1 m stage height) coursing through both channels daily, creating a unique opportunity to examine how channel complexity helps to dissipate a flood wave. Image width is approximately 150 km (2004 Landsat ETM+)

For ground verification there are two permanent gauging stations on the Saskatchewan River upstream and downstream of the avulsion node. Logistics support including boat operators and a small airport at the nearby town of Cumberland house.

Sampling requirements:
1) Required airborne measurements: water level and extent
2) Required size of the field target: ~200 km X 2 km (best) or 50 km X 2 km
3) Required temporal resolution: Repeat short-term surveys during July or August
4) Required data record length: hours to several days
5) Required accuracy: ~5-10 cm (water level); 1 m/km (slope), 2-10 m (extent)
6) Required additional instrumentation: Deploy 10-15 pressure transducers in each channel (optimal)
7) How it helps SWOT: Demonstrates new methodology and source of data for calibrating flood risk models

<u>Meltwater ponds and rivers on the Greenland Ice Sheet</u>
Inspired by speculations about the importance of supraglacial lake drainages to basal pressurization and ice flow dynamics of the Greenland ice sheet, studies of meltwater ponds and stream channels that form on top of the ice represent a very new and exciting area of hydrologic research. As of February 2010 fewer than a dozen peer-reviewed journal articles have been published about these features. First-order understanding about how they form, persist, and disappear is low. Moreover, there is lively debate about whether melt water from these abundant features on the ice sheet surface connect to the glacier bed via cracks and moulins, as theory suggests (Alley et al., 2005, see also Box and Ski, 2007), or instead remain largely detached from the basal system to either run off the ice sheet surface or perhaps refreeze within it (Catania and Neumann, 2010). Theoretical models suggest lakes as small as 250 m in diameter may contain sufficient water volume to rapidly drive hydro-fractures through 1 – 1.5 km of underlying subfreezing ice to reach the bed (Krawczynski et al, 2009). But even aside from this glaciological debate, very little basic science has been done on these hydrological features, how/where they form, the extent of their drainage organization, and other fundamental processes.

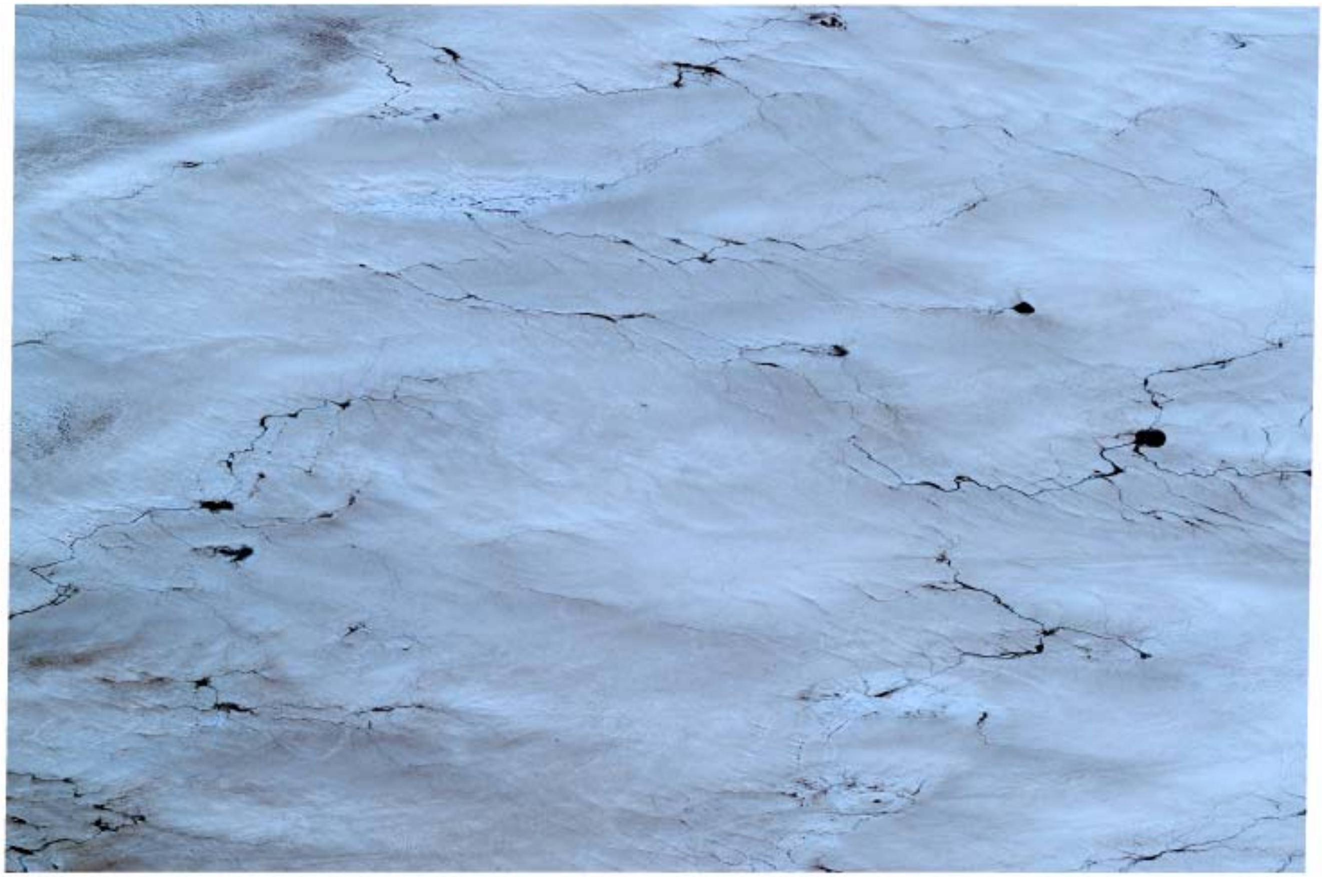

Fig. 2: Meltwater ponds, rivers and moulins (drain holes) that form on the Greenland ice sheet are arguably the least understood surface water hydrology on Earth. Of key interest is determining whether the bulk of their water penetrates through to the glacier bed, or either runs off or refreezes within the ice sheet (August 2008, Quickbird, image width approximately 16 km)

There are several ways an airborne SWOT simulator could be deployed to study these features. Melt lakes can reach diameters of several km but most are smaller than 1 km across; the width of melt channel sizes ranges from 1 m to more than 100 m across, and they can travel for many kilometers over the ice sheet surface. These features are concentrated along the western flank of Greenland extending perhaps 1500 km from north to south, and penetrate inland perhaps 200 km. One possibility would be a long "noodle"-type flight path (say 1000 X 10 km) to assess the size distribution and density of these features along the ice sheet. However, given the very poor process-level understanding of their formation, evolution, and drainage a smaller, rectangular study area (perhaps 20 X 100 km) repeated early, middle, and late in the melt season would provide the most immediate scientific payoff.

While optional, deployment of pressure transducers in streams exiting the ice sheet and possibly on the ice sheet itself would be desirable. Extensive logistics support for this exists via CH2MHill and the Kangerlussuaq International Science Support (KISS) facility at Kangerlussuaq. This town is also the primary hub for air traffic into and out of Greenland.

Sampling requirements:

1) Required airborne measurements: water level, water exent, water slope, ice sheet topography
2) Required size of the field target: variable, suggest ~20 km X 100 km
3) Required temporal resolution: Repeat in July, August, September (ideal); or July and September

4) Required data record length: 1 – 5 years
5) Required accuracy: 10 cm (water level); 1-10 m (extent); 2 m/km (slope), 1 m (ice sheet topography)
6) Required additional instrumentation: Deploy pressure transducers in outlet streams at ice margin; consider field excursion on ice sheet to verify interpretation of melt features (optional)
7) How it helps SWOT: Ideal vegetation-free environment for validation water storage and retrieval algorithms; demonstration of ice surface topography mapping

Can surface water tell us something about groundwater? (with input from Frank Schwartz, Ohio State University)

It has long been recognized that groundwater flow systems, if unconfined and in reasonably porous media, have a significant impact on surface water (e.g. Winter, 1978; 1983). Lakes and streams can recharge aquifers or be filled by them, or both if regional groundwater flow patterns vary over time. This interaction manifests itself by affecting water hydrochemistry (lakes with higher groundwater inflow are often more saline) and water level.

One locale where these surface-groundwater interactions have been studied for more than thirty years is the USGS Cottonwood Lake Study Area in North Dakota. This small collection of monitored ponds and groundwater wells is situated in the prairie pothole region, a major province of glacier-derived wetland depressions covering ~715,000 km^2 of North America. The USGS CLSA is a regional groundwater recharge area, but also contains water bodies that function as flow-through, and discharge sites (LaBaugh et al. 1987). Sixty water table wells have been installed in the USGS CLSA to monitor the regional water table position and gradient, as well as water level gauges in 17 prairie potholes (http://www.npwrc.usgs.gov/projects/clsa/studypln.htm).

An airborne SWOT simulator offers a unique opportunity to expand study of surface-groundwater interactions to much larger geographic areas than is possible from *in situ* monitoring. An appropriate study area for an airborne investigation might cover ~30 km X 150 km, with spaced flight lines (i.e. a grid formation, they do not need to overlap) roughly centered over the USGS CLSA. The campaign would be conducted over a period of seven months, from April through October which in a typical year would capture the seasonal transition from wet (snowmelt runoff) to dry by late summer. Approximately six flights would be optimal, separated by 3 weeks early in the season, and perhaps six weeks into the fall (this could be adjusted down to as low as four). Flight lines should be oriented normal to the largest topographic gradients (roughly east-west) and several lines along the long axis of the study area. One of these flight lines should pass directly over the USGS CLSA. Over a typical seven month time period, pothole lake stages might decline by 30 or 40 cm, and perhaps more where groundwater outflow is occurring in addition to evaporation, and less where groundwater is inflowing. This would be the first study to test such a hypothesis in detail. To be useful, the instrument should be able to resolve lake-stage differences of 5 to 10 cm.

Fig. 3: Regional groundwater systems have long been known to influence water levels across North America's prairie potholes, such as these near Jamestown, North Dakota. However, lack of synoptic water level data has precluded study of this at a broad geographic scale. Circles enclose what appear to be low-stage potholes, possibly suggesting areas of groundwater recharge for subsurface flow towards the N-NW. Airborne SWOT simulator measurments of water level across large areas are required to prove or disprove this hypothesis (August 2008, Quickbird, image approximately 16 km wide)

A second appropriate target to study surface-groundwater interactions is the Nebraska Sand Hills, a key recharge area supporting the irrigated agricultural economy of eastern Nebraska. Precipitation is stored in lakes and groundwater systems then migrates eastward via North Loup and Middle Loup Rivers and the Ogallala aquifer. Such a study could be conducted at the same geographic scale as above (~30 X 150 k), but by expanding the flight grid coverage to approximately 200 X 350 km could sample essentially all Nebraska Sand Hills in entirety.

Sampling requirements:
1) Required airborne measurements: water level, water extent, land elevation
2) Required size of the field target: variable, suggest ~30 km X 150 km spaced grid
3) Required temporal resolution: 4-6 repeats between April and October, more often in spring
4) Required data record length: 1 – 5 years
5) Required accuracy: 5-10 cm (water level); 1-10 m (extent), 0.5 m (land elevation)
6) Required additional instrumentation: In situ data hydrologic data are already being collected by the USGS Cottonwood Lake Study Area. Other possibilities for field work include soil samples and ground-based gravity measurements to infer groundwater changes. An on-board camera would aid study of lake color as a possible second indicator of groundwater influx
7) How it helps SWOT: Algorithm development for lake storage change retrieval; prairie potholes and wetlands offer test sites to study influence of aquatic vegetation on SWOT retrievals.

Can surface water elevations tell us something about permafrost?
Like surface/groundwater interactions, the presence or absence of ground permafrost is known to influence surface water, with a general tendency to increase its prevalence especially in the spring. On average, for a given terrain type the presence of permafrost roughly doubles the abundance of lakes and wetlands (Smith et al., 2007). However, beyond this generalized rule of thumb the influence of permafrost presence/degradation upon surface water hydrology remains very poorly understood. This poses a serious knowledge gap for permafrost areas of the Arctic and sub-Arctic, places that count among the most water-rich landscapes on Earth, especially in light of climate model projections that suggest up to 90% reduction in near-surface permafrost by the end of this century (Lawrence and Slater, 2005).

A robust method for detecting the existence of subterranean permafrost from satellites does not currently exist. However, there are at least two ways that surface water levels in lakes and wetlands might provide indicators of permafrost presence and/or state of health. The first is that in a permeable, permafrost-free landscape water levels in lakes and wetlands might be expected to respond in concert to the seasonal cycle of regional groundwater table fluctuation – much like the prairie potholes described earlier. A permafrost landscape, in contrast, might be expected display many perched lakes with different absolute water surface elevations and minimal temporal variations them over the seasonal cycle. Rather than groundwater recharge/discharge, the primary driver of lake level changes in such lakes would be precipitation and evaporation, both of which are generally low in the Arctic and sub-Arctic (for this reason an unusually high vertical precision, say ~2 cm, is required for the lake water level measurements). A permafrost landscape might also see stream levels fall quicker in fall and not reappear until the spring melt, unlike groundwater-fed streams that receive persistent year-round baseflow.

The second way in which surface water levels and adjacent land elevations might tell us something about the presence and/or condition of subterranean permafrost is through the physical morphology of the water bodies themselves. For example thermokarst lakes, which grow in continuous permafrost, tend to fully occupy their basins, with water surface elevations at or very near the surrounding land surface. Thaw sinks, which imply a degradation of permafrost and possible water loss to groundwater flow, tend to have water surface elevations lower than surrounding land (Figure 4). Such elevation contrasts should be easily observed and quantified using airborne imaging altimetry.

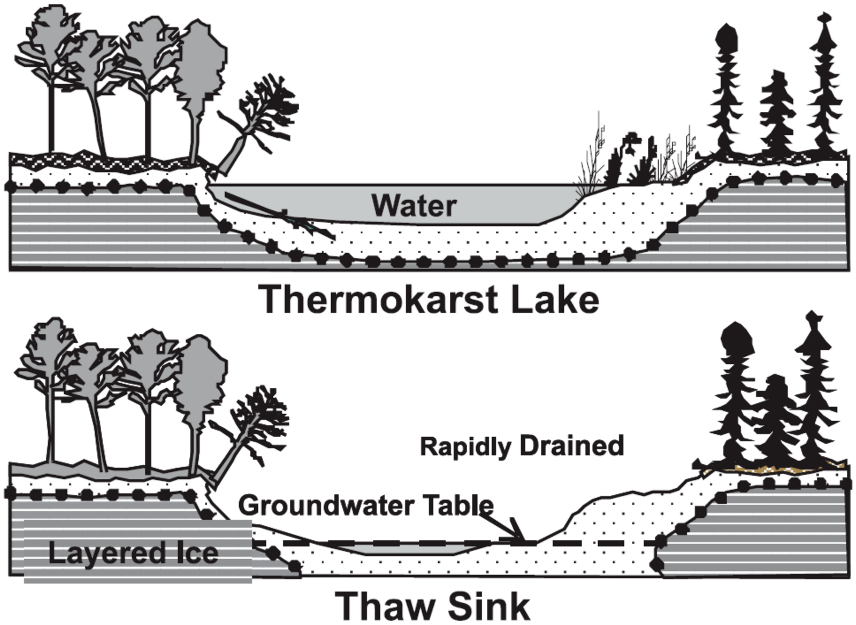

Fig. 4: Land-water elevation contrasts between a thermokarst lake, associated with continuous permafrost, and a thaw-sink, associated with degrading permafrost. Such contrasts would be directly measurable from airborne imaging altimetery (from Jorgenson and Osterkamp, 2005).

To test these ideas, a long flight line in a roughly N-S direction is preferred over the more compact study areas proposed for the prairie pothole regions. Because most permafrost maps are inferred from interpolated climate station data rather than direct observations, the current distribution of world permafrost known only broadly (e.g. Brown et al., 1997). However, by examining large geographic areas, spanning perhaps ~800 km to 1000 km in a roughly N-S direction, it is possible to capture the full range of potential permafrost conditions (i.e. from non-permafrost to isolated, sporadic, discontinuous, and continuous permafrost). An ideal locale would be the Canadian shield, following an approximately 10 km X 1000 km long flight path, originating roughly around Thunder Bay, Ontario and traversing N-NW past Churchill, Manitoba. For examining lake/wetland sensitivity to seasonal groundwater cycles, 4 – 6 flights per year between May and September would be optimal. For morphological mapping as illustrated in Figure 4, a single late summer flight (August or September) would suffice.

While not mandatory, field validation of the presence/absence of permafrost would be optimal. Logistics support to do this is available from the Churchill Northern Studies Research Center in Churchill, Manitoba. An excellent airport (former U.S. military base) is also found at Churchill.

Sampling requirements:
1) Required airborne measurements: water level, land level, water exent
2) Required size of the field target: ~1000 km X 10 km
3) Required temporal resolution: 4-6 repeats between May and September (seasonal water level fluctuations); or once (morphological mapping)
4) Required data record length: 1 – 5 years
5) Required accuracy: ~2 cm (water level); 10-50 m (extent)
6) Required additional instrumentation: Field measurements of permafrost depth (optional).

7) How it helps SWOT: Algorithm development for lake storage change retrieval; algorithm development for land elevation retrievals.

To what extent will SWOT data reduce uncertainty in flood risk mapping? (with input from Jim Smith, Princeton University, and Witold Krajewski, The University of Iowa)

Hydraulic models are used routinely across the developing world to estimate flood risk in order to plan flood defenses, reduce the risk to populations and set insurance and re-insurance premiums. In the US alone billions of dollars per year are spent on flood defense and clearing up flood damage, and these figures may increase in the future with climate change and more intensive use of floodplains. As we wish to estimate the impact of very large floods (typically with annual probabilities of 0.01 or less) that are unlikely to have been previously observed in the hydrologic record we use hydraulic models to estimate the likely water depths and velocities. However, before such predictions are made the friction coefficients in these models need to be calibrated against observed flow data from low magnitude, high frequency events that we do have records of.

In many areas of the US the only data available with which to undertake this calibration consists of water levels recorded at USGS gauging stations. This network was designed primarily with water resource management and flood forecasting applications in mind and accordingly the spacing between stations is typically many 10s of km. The network was not specifically designed for the calibration and validation of hydraulic models where we need accurate predictions of areas at risk of flooding down to the scale of individual properties (i.e. 10-100m). There is a strong danger that hydraulic models calibrated against (relatively) sparse gauging station data may be correct at the gauged locations but substantially in error elsewhere. Instead, if we wish to make detailed, property-level predictions from hydraulic models we likely need to calibrate and validate them against flow observations of a commensurate spatial resolution. The SWOT satellite will provide such data for the first time, and we can use an airborne SWOT campaign to determine their potential utility to reduce the uncertainty in the floodplain zonation maps that are routinely produced by organizations such as FEMA.

An ideal way to examine this question is to look for a site which has experienced recent extreme flooding and where excellent observed flow data, inundation observations, topographic information and models already exists. By observing low frequency flood events at such a site using an airborne SWOT simulator we can conduct numerical experiments to determine the extent to which hydraulic model calibration using SWOT data will reduce the uncertainty in flood risk predictions of design events compared to more traditional calibration methodologies. An obvious site for this experiment is eastern Iowa where devastating floods occurred in 2008 which inundated thousands of homes and businesses. These floods are being extensively studied by the University of Iowa's Iowa Flood Centre (see http://www.iowafloodcenter.org/) who have made substantial progress in data collection and modeling of this event. To complement these data we propose to use an airborne SWOT campaign during the winter flood season to image a small number of high frequency, low magnitude flood events in this system that can then be used in the numerical experiments as described above. This work will draw on the extensive local knowledge of staff at the University of Iowa to help plan the field campaign and undertake follow up modeling studies.

Sampling requirements:
1) Required airborne measurements: water level, water extent, land elevation

2) Required size of the field target: ~50km each of the Iowa and Cedar rivers
3) Required temporal resolution: 4-6 repeats between October and April on an opportunity basis to coincide with small flood waves in these systems
4) Required data record length: single overpasses
5) Required accuracy: 5-10 cm (water level); 1-10 m (extent), 0.5 m (land elevation)
6) Required additional instrumentation: largely already collected by University of Iowa. May need a need for a limited field campaign to collect any additional data necessary for modelling
7) How it helps SWOT: assessment of potential for SWOT data to reduce uncertainty in flood risk predictions and the potential utility of SWOT data for FEMA, state planners, insurers and re-insurers.

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