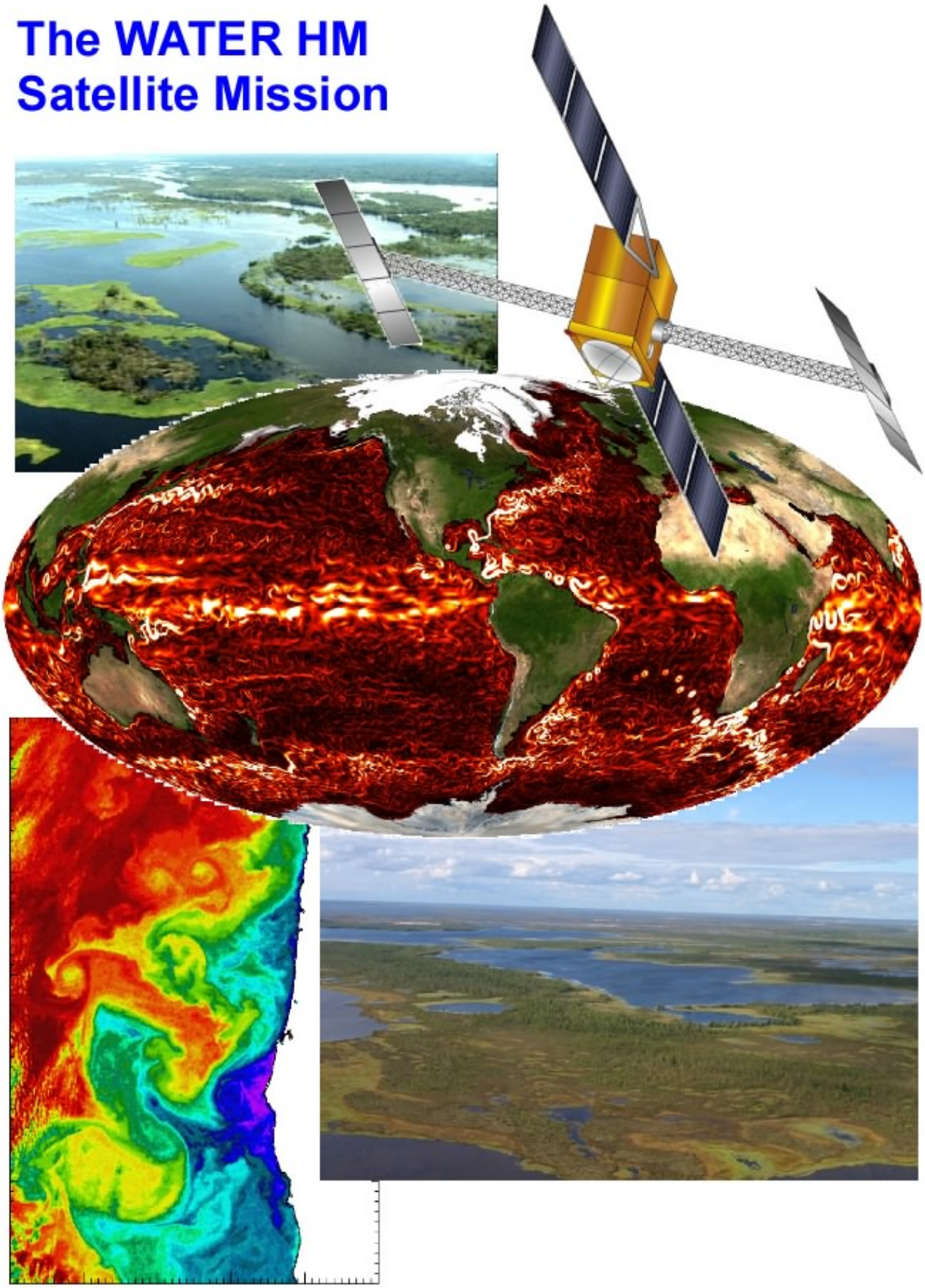
The WATER HM Satellite Mission



WATER HM: The Water And Terrestrial Elevation Recovery Hydrosphere Mapper Satellite Mission

First Mission Document for the WATER HM Mission

Preface:

This document is not a proposal; rather it is a briefing on the status of the science and technology in support of the advanced wide-swath altimeter. The document serves to collect the variety of thoughts, presentations, proposals, and publications already made regarding the potential for a joint-science hydrology and oceanography satellite mission. Both the U.S. and French space agencies, NASA and CNES, recognize the importance of WATER HM (Water And Terrestrial Elevation Recovery Hydrosphere Mapper) and are now investing resources toward its success. NASA and CNES have a rich, 20 year history of partnership in radar altimetry which will now be further advanced through WATER HM.

This document was initially called-for at a meeting held in Barcelona, Spain on July 25th 2007 (details of that meeting are available at http://earthsciences.osu.edu/water/ click on the "meetings" button). Please feel free to comment and edit this document, but do not distribute without referencing.

The WATER HM web page http://earthsciences.osu.edu/water/ contains more information. WATER HM participants are noted at this web page and include over 200 people from 30 countries. We welcome everyone to join and participate in WATER HM.

Sincerely,

Doug Alsdorf
August 20, 2007
alsdorf.1@osu.edu

Cover image includes photos by Laura Hess (Amazon floodplain in upper left) and Karen Frey (Arctic lakes in lower right) with artistry by Karen Wiedman (the WATER HM satellite). The ECCO-2 JPL ocean current model is shown in the center and sea-surface temperatures along the California coast are plotted in the lower left.

WATER HM

The Water And Terrestrial Elevation Recovery Hydrosphere Mapper Satellite Mission

First Mission Document for the WATER HM Mission

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Summary

Two Core Issues Addressed by One Satellite Mission

Surface fresh water is essential for life, yet we have surprisingly poor knowledge of its variability [e.g., *NSTC,* 2004; *Shiklomanov et al.,* 2002]. Key societal issues regarding the susceptibility of life to drought and floods cannot be answered with the current global networks designed to observe river discharge but not flood events.

Climate change is directly connected with the world's oceans, which are the largest heat reservoir in the climate system. Ocean circulation and ocean-atmosphere interaction fundamentally drive weather and climate variability. Yet, the global ocean current and eddy field (e.g., the Gulf Stream) that affects ocean circulation is poorly known [*Chelton and Freilich,* 2006].

WATER HM is a swath-based interferometric-altimetry mission designed to acquire elevations of ocean and terrestrial water surfaces at unprecedented spatial and temporal scales with major outcomes related to the global water cycle, water management, ocean circulation, and the impacts of climate change.

Scientific Objectives

WATER HM will contribute to a fundamental understanding of the terrestrial branch of the global water cycle by measuring water storage changes in all wetlands, lakes, and reservoirs and by estimating discharge in rivers. The global, high-spatial resolution measurements of ocean surface topography will allow derivation of all ocean currents and eddy fields as well as mappings of mass transport along coastal regions.

Societal Objectives

WATER HM will facilitate societal needs by mapping ocean currents which are needed for shipping and pollutant transport; analyzing the effects of ocean eddies on marine ecosystems and fisheries; improving hurricane forecasts; improving our understanding of flood hazards and the ability to forecast floods; mapping space-time variations in water bodies that contribute to disease vectors (e.g., malaria); and provide freely available data in near-real time on the storage of water available for potable and other human uses.

Measurements Required

WATER HM will provide nearly weekly measurements of water surface elevations (h) for the oceans, wetlands, rivers, lakes, and reservoirs around the world. Each successive h measurement will allow computation of spatial variations and temporal changes in elevation hence allowing computations of ocean current velocity, relative vorticity, eddy induced momentum flux, terrestrial water storage changes, and hydraulic gradients which are a primary determinant of river discharge.

Technology Description

The primary WATER HM instrument is an interferometric altimeter which has a rich heritage based on (1) the many highly successful ocean observing radar altimeters, (2) the Shuttle Radar Topography Mission, and (3) the development effort of the Wide Swath Ocean Altimeter. It is a near-nadir viewing, 120 km wide, swath based instrument that will use two Ka-band synthetic aperture radar (SAR) antennae at opposite ends of a 10 m boom to measure the highly reflective water surface. Interferometric SAR processing of the returned pulses yields a 5 m azimuth and 10 m to 70 m range resolution, with elevation precision of ± 50 cm. Polynomial based averaging over areas less than 1 km^2 increases the height precision to less than ± 1 cm.

Introduction: Physical Oceanography and Surface Water Hydrology

Satellite radar altimetry has revolutionized oceanography by providing global measurements of ocean surface topography (OST, e.g., *Fu and Cazenave*, 2001). Topex/Poseidon (T/P) and Jason-1 satellite missions have been particularly key for producing long-term measurements of the large scale ocean circulation as well as global and regional sea level change. These measurements have led to a number of discoveries such as the role of oceans in the climate system, on the El Niño and La Niña phenomena, on present-day sea level rise, etc. (most major results are summarized in the book edited by Fu and Cazenave, 2001). A critical drawback of nadir altimeters such as T/P and Jason-1, however, is the 200 to 300 km spacing between orbital tracks that prevents sampling of two-dimensional currents. Thus oceanic mesoscale processes, which contain 90% of the ocean kinetic energy, and complex coastal phenomena are almost completely unmeasured.

Given societies' basic need for fresh water, perhaps the most important hydrologic observations that can be made are of the temporal and spatial variations in water stored in rivers, lakes, reservoirs, floodplains, and wetlands. There is a widespread recognition of the need for better observations and understanding of surface water distribution globally [e.g., *Marburger and Bolten,* 2004, 2005; *United Nations,* 2004; *International Working Group on Earth Observations,* 2005; *National Science and Technology Council,* 2004]. This is especially problematic considering that over one third of the world's population is not served by adequate supplies of clean water [*Gleick,* 2003].

In contrast to ocean observations, surface fresh water measurements are limited mostly to in-situ networks of gauges that record water surface elevations at fixed points along river channels. Globally, we do not know the spatial and temporal distribution of water stored on the land surface and moving through river channels with any but the crudest accuracy. Furthermore, water movement in wetlands and across floodplains throughout the world is essentially unmeasured, thus our understanding of flood processes is limited.

More recently, nadir-viewing satellite altimetry has also been applied to measuring surface water height variations on lakes, rivers and wetlands [e.g., *Birkett,* 1998, and reviews by *Cretaux and Birkett,* 2006, *Calmant and Seyler,* 2006]. Here again the large inter-track spacing is totally inadequate for terrestrial hydrology [*Alsdorf et al.,* 2007a]. Moreover, current altimetry missions are designed, and hence optimized, for ocean surfaces, which leads at best to noisy data over inland waters, or sometimes no data acquisitions at all.

The physical oceanography and surface fresh water hydrology communities have joined together in recognizing the potential of high-resolution, spaceborne measurements of water surface elevations. Based on the heritage of the Shuttle Radar Topography Mission (SRTM), scientific and technical studies at JPL over the past 7 years have refined the wide-swath interferometric altimetry concept for high-resolution sampling of OST [*Fu and Rodriguez,* 2004]. More recently, this technique has demonstrated its high potential for mapping terrestrial surface waters [e.g., *LeFavour and Alsdorf,* 2005; *Kiel et al.,* 2006; *Alsdorf et al.,* 2007a; *Romeiser et al.,* 2005].

Important Questions in Physical Oceanography

Lacking more detailed measurements than are currently available, we are unable to address the following issues in physical oceanography:

(1) The strongest currents of the ocean such as the Gulf Stream and Kuroshio have a

spatial scale of a few tens of kilometers in the cross-stream direction. These currents and their meanders and eddies carry 90% of the kinetic energy of the ocean. They are directly coupled to weather patterns and climate change by distributing heat and mass in the ocean. Numerical experiments suggest

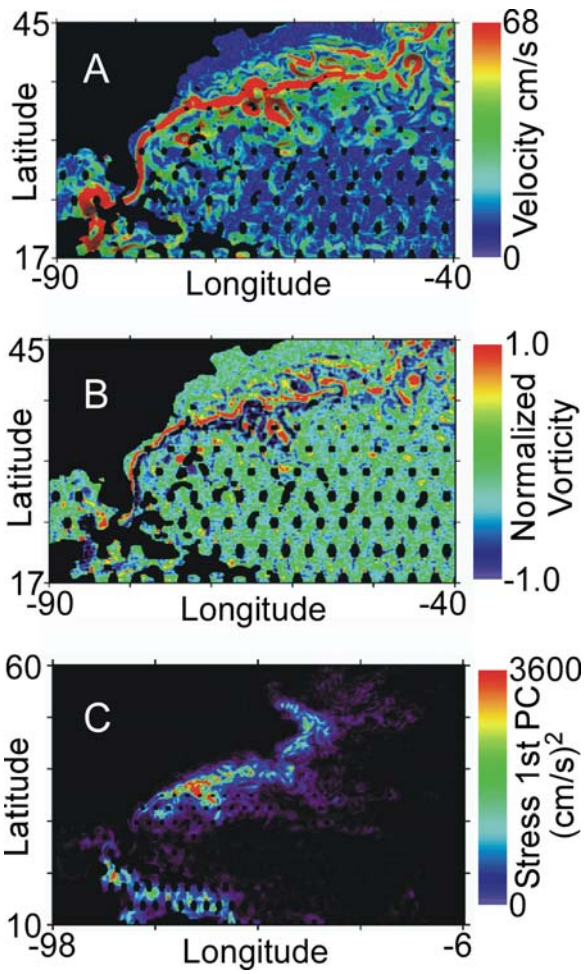

Figure 1: Model based simulation of the Gulf Stream [*Maltrud & McClean,* 2005]. Example ocean data products for WATER HM include measurement of (a) vector geostrophic velocity (b) relative vorticity and (c) Reynolds stress tensor. These measurements would be available for every mapped location of the ocean surface, unlike conventional altimetry, where they can only be obtained at the orbit cross-overs. The figures presented here reflect the coverage of a 10-day repeat orbit. Orbits with longer repeat periods will diminish the coverage gaps.

that realistic simulation of oceanic heat transport can only be achieved from models that are able to fully resolve these scales (Figure 1, *Maltrud and McClean,* 2005). Thus, perhaps the most important question we face is: *What is the variability in eddy currents and the resulting impact on global climate and weather?*

(2) Upwelling and cross-shelf transport of mass, salt, and nutrients in the coastal oceans occur at spatial scales of order 10 km or less, which are presently not sampled globally. Unanswered questions include: *What are the effects of coastal circulation on marine life, ecosystems, waste disposal, and transportation.*

(3) Observations of ocean surface topography (OST) have been used in conjunction with models to compute the "heat potential" for the prediction of the intensity of hurricanes. The spatial structure of hurricanes is complex and requires high-resolution observations with broad spatial coverage. Merging of multiple satellite altimeter observations resulted in a 21% improvement in the 96 hour lead-time forecast of Hurricane Ivan [*Mainelli et al.,* 2007]. NOAA's National Hurricane Center is now routinely using altimeter data for hurricane forecasts, but the resolution of the data is likely to decrease due to the lack of overlapping multiple altimeter missions in the future. An essential question emerges: *How can hurricane lead-time forecasts be improved?*

Important Questions in Surface Water Hydrology

Existing in situ networks, notwithstanding that they have served well water development needs in the industrialized world, do not provide an adequate global knowledge base of the changes in the volume of water stored and flowing in rivers, lakes, and wetlands [*Alsdorf et al.,* 2007a]. Because measurements are few and poorly distributed,

questions that remain in terrestrial hydrology include the following:

(1) The terrestrial water balance for a river basin equates precipitation minus evaporation with discharge and storage changes. These terms are known with varying accuracy and are typically only balanced with long-term averaging and in the absence of trends – a condition that often is not met in the presence of a changing climate. For example, lakes are disappearing in parts of Siberia, which is essentially a long-term manifestation of changes in surface storage, despite slight increases in precipitation [*Smith et al.,* 2005]. But, we do not understand whether the cause is increased evapotranspiration, increased runoff, or both. In other regions of the world, the water balance in hydrographic basins is highly dependant on human activities such as river dam building and irrigation. Here again, we do not know how these anthropogenic factors affect regional hydrology. The resulting fundamental question is, *What is the spatial and temporal variability in the world's terrestrial surface water storage and how can we predict these variations more accurately?*

(2) Water flow through wetlands and floodplains is spatially and temporally complex [e.g., *Alsdorf et al.,* 2007b; *Lincoln,* 2007]. These flows are a key element of wetland ecology and floodplain geomorphology because they transport nutrients and carbon as well as erode and deposit sediments. For example, CO_2 evasion to the atmosphere from wetland waters has recently been identified as an important tropical carbon source [*Richey et al.,* 2002]. The amount of water stored on floodplains is not well known, leaving open questions regarding these wetland processes and related flood hazards. Thus, a basic question is: *How much water is stored on a floodplain and subsequently exchanged with its main channel?*

(3) How we manage water as a global resource is an important issue facing society. Surface water is the primary source of potable water for much of the world's population, yet we are unable to predict its availability accurately, especially for many of the world's river basins that cross international boundaries. Associated societal questions include: *What are the policy implications that freely available water storage data would have for water management? Can health issues related to waterborne diseases be predicted through better mappings?*

These six issues exemplify a broad set of unanswered questions and unmet needs that also include biogeochemistry, ocean bathymetry, and applications such as coastal and river navigation. For example, the need for operational nowcasts and forecasts of the coastal ocean circulation arises from the heavy human utilization of the coastal zone – for fishing, transportation, recreation, waste disposal, and habitation; and for protection of life and property under extreme weather conditions.

Measurements Required to Address the Questions

Spaceborne measurement goals for next-generation radar altimetry are driven by the science and applications questions posed above. The intent is not to replace in-situ observations, rather to complement them with fundamentally new types of data. Essentially, the equations of flux and mass conservation used in both physical oceanography and terrestrial hydrology require measurements of water surface elevations (h), temporal changes in water levels (dh/dt), water slope (dh/dx), and their spatial extents.

The oceanic, fluvial, and wetland processes described above have complex two-dimensional, changing spatial patterns that are not adequately sampled by existing profiling altimeters or point-based, in-situ

observations. Oceanic, fluvial, and wetland processes operate over a continuum of spatial scales ranging from 100's of kilometers to less than a 100 m (e.g., the width of a river channel). Temporal variability is similarly broad with annual and semi-annual flood waves in the Amazon and Congo basins, respectively, to daily tidal fluctuations.

Centimetric height and slope accuracy for both oceans and terrestrial surface waters is needed. For example, because the slope of the ocean surface is proportional to current velocity, the required OST slope accuracy is 1 cm over 100 km for a velocity accuracy of 1 cm/sec at mid latitudes (1 cm over 400 km at 10 degree latitude). Slope is an indicator of surface velocity in rivers, for which the lowest slopes are about 1 cm/km. The vast size of tropical and Arctic wetlands allows for large storage changes with just centimeter-scale temporal variations in water surface heights.

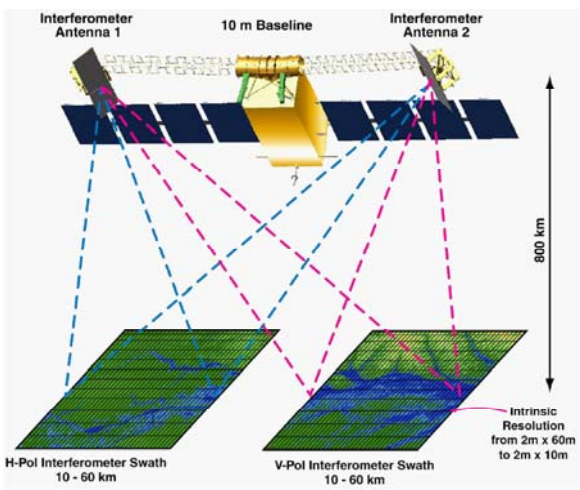

Figure 2: Conceptual view of KaRIN, the Ka-band Radar Interferometer, an interferometric altimeter. Maximum incidence angle is 4.5º, thus the instrument operates very near nadir where water surfaces yield strong radar returns. At Ka band, the interferometer will penetrate clouds and relies on subtle canopy openings to penetrate to any underlying water surfaces (openings of only 20% are sufficient). Spatial sampling resolutions are noted in the text. Height accuracies will be ±50 cm for individual "pixels" thus centimetric accuracies are achieved through polynomial averaging methods.

Wide-Swath Altimetry

These sampling requirements for innovative applications in hydrology and oceanography can be addressed with spaceborne wide-swath interferometric altimetry. The wide-swath technology proposed for WATER HM is a Ka-band Radar INterferometer (KaRIN, 0.86 cm wavelength, Figure 2) that has been developed from the efforts of the Wide Swath Ocean Altimeter (WSOA; *Fu,* 2003; *Fu and Rodriguez,* 2004). KaRIN is essentially a smaller version of SRTM with two Ka-band SAR antennae at opposite ends of a 10 m boom and both antennae transmitting and receiving the emitted radar pulses along both sides of the orbital track. Look angles are limited to 4.5º providing a 120 km wide swath. A 200 MHz bandwidth achieves cross-track ground resolutions varying from about 10 m in the far swath to about 70 m in the near swath. A resolution of about 5 m in the along track direction is derived by means of synthetic aperture processing.

The KaRIN design improves upon SRTM's meter-scale height measurements, but thermal noise limits accuracies to ~0.5 m for 10 m sized pixels. These errors can be reduced by averaging or fitting polynomials to the h values [e.g., *LeFavour and Alsdorf,* 2005]. For example, Figure 3 presents the expected height and slope performance over rivers of various widths and for a range of water surface RMS slopes (root mean squared, which governs water surface brightness). It was assumed for this figure that at least 10 km of the river reach could be imaged and fit with a linear polynomial. It is expected that KaRIN will provide better than 5 cm accuracies for river widths of 30 m and greater.

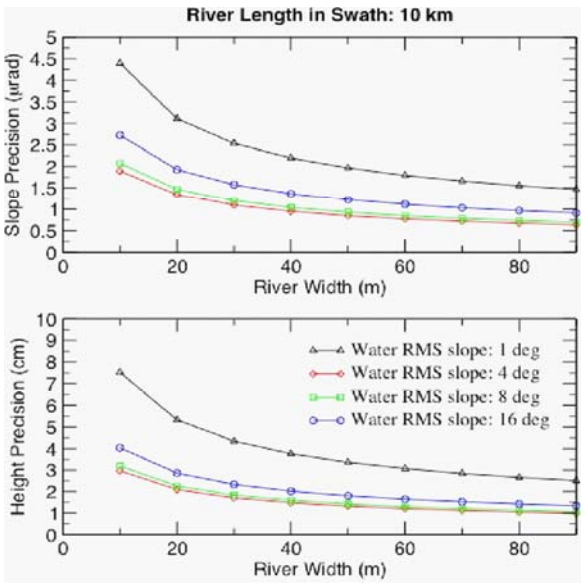

Figure 3: Height and slope precision of the KaRIN interferometer. Height and slope estimates are made by using the radar image to isolate water bodies and fitting a linear height change over the swath. Precision depends on water brightness and the length and width of the imaged water body.

The appendix contains more details regarding KaRIN, data processing, and performance.

Why is Wide-Swath Altimetry the Best Option?

Addressing the science questions noted above requires both global and local coverage [e.g., *Alsdorf et al.,* 2007a; *Fu and Cazenave,* 2001]. Globally, conventional nadir altimeters have large spatial gaps between orbital tracks leaving many terrestrial areas and oceanic processes unmeasured. Examples include hundreds of thousands of lakes or tributaries that fit between tracks, coastal zones with their complex and extensive shorelines, ocean eddies, etc. Locally, the hydraulics of wetlands and floodplains have complex flow patterns that change on scales of less than a kilometer. These flows help control the impact of floods. Ocean eddies have flows that, in their cross-stream direction, are often less than 10 km. Global, high-spatial resolution elevation mapping is thus required. Considering all of the in-situ, airborne, and spaceborne elevation measurement methods, the only practical solution is the KaRIN wide-swath instrument.

Two primary differences in sampling requirements between oceanic and terrestrial surface waters are complementary and do not require any significant compromise:

(1) Temporal sampling over the oceans must avoid aliasing tidal amplitudes into longer frequencies that would then appear as erroneous ocean circulation signals [*Parke et al.,* 1987]. For hydrology, such aliasing issues are not important because river flows and waters stored in wetlands do not have elevations that systematically vary on such short time scales. Although an orbit repeat cycle needs to be longer than 16 days to cover most of the earth's surface, the swath coverage permits revisits to any given location twice per repeat cycle and much more often for high-latitude regions. Tropics could be sampled three times per month and Arctic regions north of 55ºN about twice per week with a 21 day repeat orbit.

(2) Over the oceans the required spatial resolutions approach 1 km for sampling coastal currents. Lakes and rivers, in contrast, are much smaller and require sub-100m samplings. For example, a profiling altimeter in a 10-day orbital repeat cycle misses three quarters of all lakes in the world because lake sizes often fit between orbital tracks [*Alsdorf et al.,* 2007a]. An orbital inclination of 78º ensures coverage of all terrestrial water surfaces.

Thus, temporal sampling is dictated by oceanographic concerns whereas the ultimate spatial resolution is a function of terrestrial surface water issues, primarily river channel width.

The WATER HM Science Working Group

WATER HM is a collegial and cooperative union of two sciences: physical oceanography and surface water hydrology [*Fu and Rodriguez,* 2004; *Alsdorf and Lettenmaier,* 2003; *Alsdorf et al.,* 2007a]. A great deal of progress has been made since the 1992 launch of Topex/Poseidon. Radar altimetry has demonstrated that centimetric height accuracies are achievable over the open oceans from combined use of C-band and Ku-band nadir altimeters. Spaceborne interferometric swath altimetry has proven meter-scale height accuracies over inland water surfaces at both C-band and X-band via SRTM operating at 30º to 50º off-nadir angles [Figure 4; *Kiel et al.,* 2006].

Significant technology investment to develop the Wide-Swath Ocean Altimeter has demonstrated a 6m mast and 2.5m Ku-band reflectarray; characterized the effect of spacecraft dynamics and heating on the electronics, mast and antennae; developed on-board processing for real interferometric apertures; and determined how to design and calibrate the phase requirements of the interferometric channels to the stringent required values.

The scientific and applications communities have also made advances. Topex/Poseidon and the Jason altimeter series are joint efforts of CNES and NASA with large international participation and thousands of publications (http://sealevel.jpl.nasa.gov; publications are noted at http://sealevel-lit.jpl.nasa.gov/science/search-results.cfm). Surface water remote sensing has ongoing community involvement in Europe (http://www.legos.obs-mip.fr/soa/hydrologie/hydroweb/) and in the U.S. (http://earthsciences.osu.edu/swwg). Groups from both the oceanography and surface water hydrology communities proposed wide-swath technology to the U.S. National Research Council's Decadal Survey of Earth Science and Applications from Space (www.nap.edu/catalog/11820.html). These efforts are now combined to form the Water And Terrestrial Elevation Recovery Hydrosphere Mapper (WATER HM) satellite mission concept. WATER HM is selected by the NRC Decadal Survey as one of 17 mission concepts having the highest priority observations (the Decadal Survey used the name "SWOT", Surface Water and Ocean Topography).

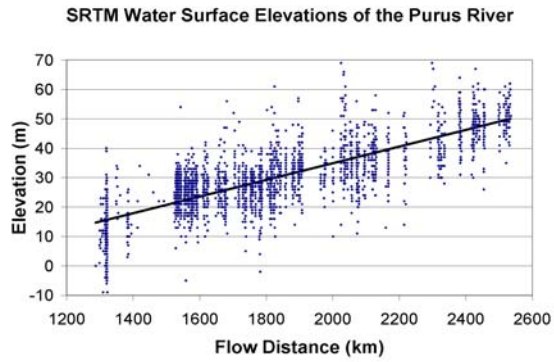

Figure 4: Water surface elevations of the Purus River, Amazon Basin. SRTM C-band water surface elevation data (blue dots) over the river yield a slope of 2.83 cm/km, determined from a linear fit (black line) to the SRTM data. Elevation standard deviation after removing the linear trend is 7.47 m. This scatter is larger than land surface elevations partly because the antennae were offset by ~7 m in the along-track direction thus making the interferometric phase sensitive to water surface velocity [e.g., *Kiel et al.,* 2006]. Water surface elevation accuracies of WATER HM are designed to be at least an order of magnitude better than SRTM.

Priorities for the joint community are focused on cost tradeoffs to finalize the WATER HM design as follows:

(1) Refinements to the orbit configuration require updated tidal aliasing studies and the study of measurement subcycles highlighting swath altimetry. Mission costs vary with orbit altitude and power management requirements which depend on details of the orbit configuration. Studies of

the best trade between orbital parameters and their effect on tidal aliasing, repeat coverage, and mission cost are thus required for assessing the performance over a wide range of orbits.

(2) Radiometers are typically used on conventional altimetric missions to correct wet troposphere errors in observed ocean heights, which have a standard deviation on the order of 5 cm but can have peak values on the order of 30 cm. The use of radiometers for correcting over land is not currently feasible. However, in contrast to the ocean, the land surface itself (which does not have long wavelength cm scale changes) as measured by the SRTM mission or other means, can be used for calibration of tropospheric errors in the absence of strong fronts. In the ocean coastal zones, however, the radiometer will suffer from the effects of land contamination and will require study to determine how these corrections will be made (e.g., perhaps accuracy can be improved using meteorological forcasting).

(3) High resolution spatial sampling is required over inland waters which results in increased data downlink rates. Costs increase with higher spatial resolution. The optimal sampling occurs where an acceptable number of small rivers remain unsampled.

In addition to oceanography and terrestrial hydrology, the proposed measurements will break new ground for studying the dynamics of estuary processes and will provide new information about marine gravity, ocean bathymetry, and glacier and sea ice. We welcome participation from the broad earth science community as the final WATER HM mission design proceeds (http://earthsciences.osu.edu/water).

Appendix: The KaRIN Instrument and WATER HM Satellite

To meet the sampling and accuracy requirements outlined above, the following suite of instruments, in addition to KaRIN, need to be flown in the same platform: a 3-frequency microwave radiometer; a nadir looking, dual-frequency C- and Ku-band radar altimeter; and a GPS receiver.

The nadir gap between KaRIN's swaths would be filled with the nadir looking altimeter, similar to the Jason or OSTM altimeters, but with the capability of doing synthetic aperture processing to improve the along-track spatial resolution. In addition to providing nadir coverage, the nadir-looking instrument would be able to collect during rain and provide data for the calibration of the Ka-band interferometer.

The 3-frequency radiometer would be used for the estimation of the wet tropospheric delay along the nadir direction, as has been done for the TOPEX and Jason Altimeters. Finally, also as in TOPEX and Jason, the GPS receiver would be used to obtain a centimeter level precision orbit. As with the nadir altimeter, we envision using identical radiometers and GPS receivers as those used for the OSTM mission, as those will be sufficient for meeting the science requirements.

Details of the KaRIN Instrument

Conventional altimeters use ranging measurements, which require additional *a priori* assumptions (e.g., the first return is from the nadir direction) in order to obtain heights and location measurements. In addition, because altimeters are nadir looking instruments, they can only achieve limited across-track spatial resolution, at best on the order of ~1 km. These limitations of radar altimetry can be overcome by the introduction of a second antenna to achieve triangulation by measuring the phase difference between the radar channels [*Rodriguez and Martin, 1992; Rosen et al., 2000*], a technique called synthetic aperture radar interferometry (IFSAR). This technique is quite mature and has been demonstrated from airborne

platforms, and most notably from space by the SRTM, where two IFSARs (at C and X-bands) produced global data with an accuracy of a few meters.

In order to achieve centimeter accuracies, a few changes to the SRTM design are required. The major contributor to height errors is the lack of knowledge of the interferometric baseline roll angle: an estimation error of $\delta\theta$ will result in a height error $\delta h = x\delta\theta$, where x is the cross track distance. Clearly, the error will be reduced if the swath cross-track distance, or, equivalently, the radar look angles are reduced. In SRTM, the look angle varied from about 20º to about 60º. We propose to limit KaRIN's maximum look angle to about 4.5º, which will reduce the outer swath error by about 14 times, compared to the SRTM outer swath attitude error. A similar reduction applies to errors due to phase, since the two errors have similar angular signatures [*Rodriguez and Martin, 1992*].

The reduction in look angles entails a reduction in swath, from 220 km for SRTM, to about 50 km (from 10 km to 60 km in cross-track distance), for the KaRIN instrument. In order to mitigate this loss in coverage, the instrument looks to both sides of the nadir track to achieve a total swath of 120 km. The isolation between the two swaths is accomplished by means of offset feed reflectarray antennas which produce beams of orthogonal polarizations for each swath. This technology was developed for WSOA, and the antennas have been prototyped and their performance demonstrated.

The height noise of the instrument is proportional to the ratio between the electromagnetic wavelength (λ) and the interferometric baseline (B). For SRTM, a 63 m baseline was required to achieve the desired height accuracy using a wavelength of 5.6 cm ($\lambda/B \sim 8.9\text{x}10^{-4}$). Such a large structure entails large costs. In order to reduce the instrument size, KaRIN uses a smaller wavelength (Ka-band, λ=0.86 cm), and reduces the interferometric mast size to 10 m ($\lambda/B \sim 8.6\text{x}10^{-4}$). The technology for a 10 m interferometric mast capable of meeting the stringent mechanical stability required for centimetric measurements has been developed by Able Engineering (SRTM mast manufacturer) in support of the WSOA technology development.

Height noise can be reduced by averaging neighboring image pixels. SRTM averaged about two pixels in order to achieve a 30 m spatial resolution with a meter level height noise. To achieve centimetric height noise, and also to produce images of the water bodies, an increase in the intrinsic range resolution of the instrument is required. Using a 200 MHz bandwidth system (0.75 m range resolution) achieves ground resolutions varying from about 10 m in the far swath to about 70 m in the near swath. A resolution of about 5 m (after onboard data reduction) in the along track direction is derived by means of synthetic aperture processing. Noise reduction is achieved by averaging over the water body, as described below. The increase in bandwidth requires an appropriate amount of power to be available: building on heritage from the CloudSat mission EIK technology achieves an appropriate SNR for centimetric accuracies.

Figure 2 shows a conceptual implementation of the instrument and system parameters are noted in Table 1. Note that to achieve the desired resolution, SAR processing must be performed. Current processing technology is not yet able to accommodate the required computations onboard. Therefore, after passing through a data reduction presuming filter, the raw data are stored and subsequently downlinked to the ground. The data downlink requirements can be met with four 300Mbit/sec X-band receiving stations.

Table 1: Key parameters for KaRIN

Parameter	Units	Value
Mass	kg	150
Frequency	GHz	35
Peak Transmit Power	W	1500
Duty Cycle	%	2.65
RF Operating Power	W	790
Operating Time/Orbit	%	40
Average Power/Orbit	W	316
Raw Data Rate	Mbits/s	504
Data Volume/Orbit	Gbytes	76
Antenna Length	m	4
Antenna Width	m	0.2
Boresight Look angle	deg	3.5
Baseline Length	m	10
Orbit Height	km	800
One-Sided Swath	km	50
Number of Swaths		2
Range Resolution	m	0.75
Azimuth Resolution	m	5

Data Processing and Instrument Data Products

After IFSAR processing, the instrument data products will consist of a radar *interferogram*: a complex image in range and along-track direction whose amplitude is proportional to the scene scattering strength, and whose phase can be used to determine the 3-dimensional geolocation of each pixel imaged [*Rodriguez and Martin,* 1992]. Figure 5 shows an example of simulated returns for the KaRIN instrument over small tributaries to the Amazon. The image brightness represents backscatter strength, and the rivers and flooded areas can be clearly differentiated. The image color represents the interferometric phase, which can be used to retrieve the look direction.

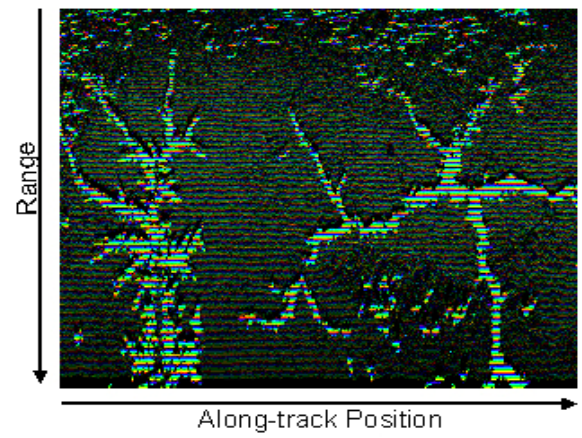

Figure 5. Simulated Interferometer return. The interferometer return signal contains both radar brightness (for water boundary delineation) and phase (color) for height estimation. Image geolocation accuracy given by timing accuracy, not platform attitude, unlike an optical imager.

After interferogram formation, an image classifier will be run over the brightness image to retrieve a water mask. This water mask will then be used to average the water and land data separately (to avoid height contamination), thus reducing speckle noise. Finally the data will be geolocated and calibrated (see below). The level 2 terrestrial data products will thus consist of topographic snapshots of the water surface together with a co-registered water mask. The topographic data can then be used to measure h and $\partial h/\partial x$ over the water body, while the multi-temporal data collected over multiple revisits can be used to measure $\partial h/\partial t$. In addition, away from mountains in regions of low relief, it will be possible to derive topography for land surfaces. This will allow WATER HM to obtain unprecedented topographic mapping of flood plains by averaging the height data over the mission lifetime.

KaRIN Instrument Performance and Calibration

IFSAR errors can be separated into random errors, which are independent from pixel to pixel, and systematic errors, which

consist of residual tilts over the entire swath. In addition to these instrumental errors, additional range errors can be caused by media delays due to wet and dry tropospheric delays and ionospheric delays (although these last are small at Ka-band).

Random errors are due to thermal noise in the system, and cannot be compensated. For the WATER HM system, their magnitude will depend on wind speed over the water surface, but, as an order of magnitude, they are about 0.5 m for 10 m pixels. These errors can, however, be reduced by averaging and typically they will decrease linearly with the surface area used for the averaging. Thus, an option to decrease the effect of random errors is to fit the water surface with a polynomial as a function of downstream distance for rivers [e.g., *LeFavour and Alsdorf,* 2005], or direct averaging over the water area for standing bodies of water.

As an illustration of KaRIN's precision, Figure 3 presents the expected height and slope performance of WATER HMover rivers of various widths and for a range of water surface RMS slope (which governs water surface brightness; RMS = root mean squared). It was assumed for this figure that at least 10 km of the river reach could be imaged for polynomial fitting. Detailed coverage studies show that this situation will occur with a 95% probability. It is clear that the proposed instrument precision exceeds the science needs outlined above.

Residual surface tilts due to lack of knowledge in the baseline roll angle will be responsible for the bulk of the systematic errors. Current star-tracker technology is capable of ~1 arcsec accuracy (e.g., Ball CT-602 used in ICESat). This will result in a residual cross-track height error ranging from about 5 cm in the near swath to about 30 cm in the far swath (or, equivalently, a slope bias of about 5μrad (0.5cm/km) which should be compared to the 10μrad (1cm/km) characteristic of the smallest slope rivers, such as the Amazon. Below, we outline a calibration method for removing these errors.

Media delays due to the dry troposphere and the ionosphere can be compensated to a ~1 cm accuracy by using GPS ionospheric maps and metereological pressure fields. Wet tropospheric delays, which can be corrected with a 3-frequency radiometer for ocean altimetry, cannot be compensated over land due the intrinsic variability of surface emmisivity. The magnitude of these delays can be as large as 30 cm, but the RMS variability is typically in the range between 3 cm and 5 cm. The typical scale length of these delays, as observed by the TOPEX and Jason altimeters, is on the order of ~100km, so for KaRIN the main impact will be a range error of < 5cm, with a residual slope of a few centimeters.

The two errors discussed above can be characterized as height biases with long wavelength slopes. These residual errors can be corrected using multiple calibration techniques. First, data collected by ascending and descending passes can be required to be consistent over the land surface. Second, control points can be generated by the nadir altimeter at river and lake crossings, since the nadir altimeter is very insensitive to roll errors. Finally, a global adjustment can be required to match a topographic map. This topographic map could be the SRTM DEM, which is available for all latitudes smaller than 60º, or the topographic map which will be obtained by averaging the data collected by WATER HM over land. Since roll and troposphere are uncorrelated from pass to pass, the average error will be reduced by an order of magnitude after about 100 passes, or after about 2 years of data collection. All of these techniques have been used in the SRTM

mission whereas cross-over minimization is routine for altimetric missions such as TOPEX, Jason, or ICESat.

We have performed a simulation of the residual long wavelength errors after calibration, assuming that only a pre-existing topographic map with a posting of 90 m and a random height error of 2 m is used for calibration (consistent with SRTM data quality), and found that the residual errors will be sub-centimetric if a calibration region of 60 km x 60 km is used. The calibrated data will suffer from the same long-wavelength biases as the calibration map. For the SRTM data, these biases consist of ~5m level height errors over scales of ~thousands of kilometers, or residual slopes on the order of 5μrad (0.5cm/km). Most importantly, these errors will be consistent from pass to pass, so that the surface topography time series will be consistent and the relative river stage variations can be recovered to centimetric precision.

As a final comment, we note that, due to the near nadir incidence angles of KaRIN, the penetration into vegetation canopies will be no worse than that of optical instruments, such as the ICESat laser altimeter, which have demonstrated penetration even for tropical canopies [*Harding and Jasinski,* 2004]. Since the water surface is much brighter than the vegetation, the requirement that inundation extent be detectable under vegetation canopies will be possible as long as the fraction of canopy gaps times the ratio of water to land brightness be greater than about 2. This leads to a requirement that the canopy have a fraction of gaps greater than about 20% for typical scattering situations. This situation is true for all but the heaviest canopies.

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