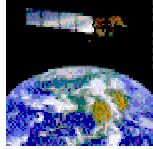


*NASA Post-2002 Land Surface Hydrology Mission
Component for Surface Water Monitoring:*

HYDRA-SAT HYDRlogical Altimetry SATellite



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Executive Summary

HYDRA-SAT (HYDRological Altimetry SATellite) is a surface water mission dedicated to the near-real time monitoring of rivers, lakes, reservoirs and wetlands. Its aim is to retrieve stage, surface velocity and along-track target widths for the determination of river discharge and inland water body volumes.

Rivers represent the primary source of freshwater for humans who additionally use these inland water bodies for transportation, food, and waste processing. On a global scale, river flow is a major component of the global water cycle, it plays a key role in the transport of dissolved and particulate materials within and from the continents, and affects the freshwater balance and the circulation of certain oceans and seas (e.g. Arctic and Mediterranean). Freshwater lakes and artificial storage reservoirs also account for more than 75% of the storage of freshwater over the land surface and climate-induced variations in natural lake levels are also among the largest changes in continental water storage. The purposeful storage, draining, and filling of reservoirs is globally significant, imparting a detectable change in the timing of continental runoff, material transport, and even the apparent rise in sea level. An ability to monitor extreme events such as drought or flood has important implications for society as well.

Our current capacity to monitor the global state of inland rivers, lakes, reservoirs, and wetlands faces several technical, economic, and institutional impediments, which collectively have resulted in explicit data restriction policies as well as substantial (i.e. multi-year) delays in data availability to the global change research community. Many remote areas also suffer from a scarcity of surface observation stations and there in general great difficulties in acquiring data in

near-real time, especially in the developing world. Even in regions traditionally endowed with rich hydrological monitoring networks, a net loss of recording stations continues to take place. Traditional data sources are thus becoming less accessible and for applications at continental and global scales, satellite-based sensors offer a feasible alternative toward obtaining near real-time data for lake/river stage and river discharge. A capacity to coherently monitor inland waters will be essential to the future development of Earth System Models, the monitoring of the biosphere, and an articulation of land-to-ocean linkages.

The HYDRA-SAT mission is designed to support several key science and operational objectives. Its primary aims are to:

- *Monitor in near-real time stage height, surface velocity and along-track target widths for major rivers, lakes, reservoirs and wetlands;*
- *Produce global data products of time varying river discharge, lake and reservoir volume variations and wetland inundation;*
- *Produce a freely accessible and timely hydrographic data set which will counteract the increasing deterioration of traditional monitoring networks, data commercialization and significant delays (up to several years) in data processing and distribution; and,*
- *Support a broad spectrum of interdisciplinary studies requiring accurate and contemporary information on the state of the hydrosphere necessary for the detection of global climate change, assessment of climate variability, and quantification of direct human impacts on the terrestrial water cycle.*
- *Provide data products that directly benefit the calibration and validation of Earth System models.*

The major technical requirements of the mission are defined by the time-varying nature of inland water bodies and a recognition of limits associated with the current fleet of satellite ocean altimeters when applied to inland waterways.

HYDRA-SAT mission specifications include the following:

- (a) River, lake, reservoir and wetland surface height data should be globally retrievable (spanning at least ± 65 deg latitude) for targets >250 m wide (rivers) or >100 km² in surface area (others) and with an accuracy of 5cm rms;*
- (b) River widths should be estimated to within 10m accuracy;*
- (c) River surface velocity should be measured to within 20 cm/s RMS accuracy*

(d) The maximum overpass repeat should be 3-7 days;

(e) River crossings should be repeatable from orbit to orbit to within $\pm 125\text{m}$ across track; and,

(f) Useful preliminary data must be processed and made publicly available in near-real time.

HYDRA-SAT is notionally based on 1) radar remote sensing system, with day/night and all-weather capability for river and lake stage and along-track width and (optionally under Scenario C) a Doppler lidar system for measurement of surface velocities day/night with a target of 50% of all-weather capability. The mission would provide a near-real time baseline set of observations from which discharge and lake volume can be deduced. Several paths to this mission are foreseen. The first (Scenario A) demands no major technology advances, but requires prime modifications to traditional radar altimeters to a) directly increase performance and accuracy of height retrievals over inland waters and b) enable the storage of raw echo data for Doppler post-processing techniques and target width determination. A second path (Scenario B) is an experimental research mission with a cost-efficient radar system allowing full interpretation of raw data, but employing new techniques to reduce the number of traditionally additional peripherals and precise orbit requirements. A third path (Scenario C) would employ Doppler lidar to measure river surface flow with high spatial resolution and accuracy, in addition to the radar altimetry from as per either Scenario A or B.

Regarding the technical requirements, the fleet of currently operating and future radar altimeters have significant limitations with respect to inland water monitoring. For example, ESA radar altimetric missions have poor temporal resolution, NASA lidar missions poor orbital repeatability and suffer from cloud contamination, and NASA/CNES radar altimeters are primarily designed for ocean applications. Through collaborative efforts with the ocean/ice communities, there is an opportunity through Scenario A for a combined program, creating a more interdisciplinary mission and ensuring maximum utilization of spacecraft operating time. However, with such a combined program, hydrological requirements must be met over land surfaces. The Scenario A framework has a launch date of 2005, a total cost of \$100M, and an intended mission lifetime range between 3-6 years. Scenario B presents no new technology challenges but has not been validated for hydrological applications. It represents a reduced cost alternative, being a dedicated hydrology-only mission operating only over land surfaces. This scenario also has a launch date of 2005 and a total cost somewhat less than \$100M. Scenario C also presents an opportunity to employ a NASA-developed technology in space for the first time. This scenario could have a launch date in the 2005 timeframe and would have a cost in the \$80-120M range, depending upon the number and type of co-manifested instruments. These scenarios combined require trade (n=10), paper (13) and field (2) studies to

address specific hydrology-related technical and science requirements. Mission-readiness appears achievable within the 2005 time frame.

1. MISSION OBJECTIVES AND AFFILIATED SCIENCE ISSUES

1.1 Primary Mission Goals

A dedicated altimetric (and surface velocity, under Scenario C) mission for inland waters will substantially improve our current capacity to monitor the status of the terrestrial water cycle. Such a capability will be essential to the future development of Earth System Models, the monitoring of the biosphere, and the definition of land to ocean linkages. The success of historic and current altimetric missions suggest that a global monitoring capacity could soon be implemented. A proposed HYDRA-SAT is presented here. Its primary aims are to:

- *Monitor in near-real time stage height, surface velocity and along-track target widths for major rivers, lakes, reservoirs and wetlands;*
- *Produce global data products of time varying river discharge, lake and reservoir volume variations and wetland inundation;*
- *Produce a freely accessible and timely hydrographic data set which will counteract the increasing deterioration of traditional monitoring networks, data commercialization and significant delays (up to several years) in data processing and distribution;; and,*
- *Support a broad spectrum of interdisciplinary studies requiring accurate and contemporary information on the state of the hydrosphere.*

1.2. Rationale and Science Questions

The scientific rationale for this proposed mission emerged from NASA planning workshops including the Post-2002 Mission Planning Workshop of NASA's Earth Science Enterprise in Easton, MD (August 1998) and a recent Land Surface Hydrology Program Mission Planning Workshop in Irvine, CA (April 1999). The science questions to be addressed are:

- *How do recorded variations in discharge, floodplain, wetland, and inland lakes reflect seasonal to inter-annual variations in water storage and fluxes within basins and sub-basins?*
- *What are the impacts of observed seasonal and interannual variations in inland waters on land-atmosphere and land-ocean linkages?*
- *What is the human impact on recorded variations in surface water storage and river discharge?*

Embedded within these questions are a host of Earth System and human dimension issues of critical importance to the analysis of global change. For instance, precipitation extremes and their attendant effects on the flooding of river corridors and wetlands can be linked to the variations in crop productivity, vulnerability of engineering structures, the mobilization sediments from erosion, and danger to both humans and human settlements. Although these issues have been examined at the local and perhaps regional scales, we currently lack an integrative picture by which to assess the global dimension of these variations in surface water. Significant delays and access restrictions characterize the current generation of global runoff data sets (**Figure 1**).

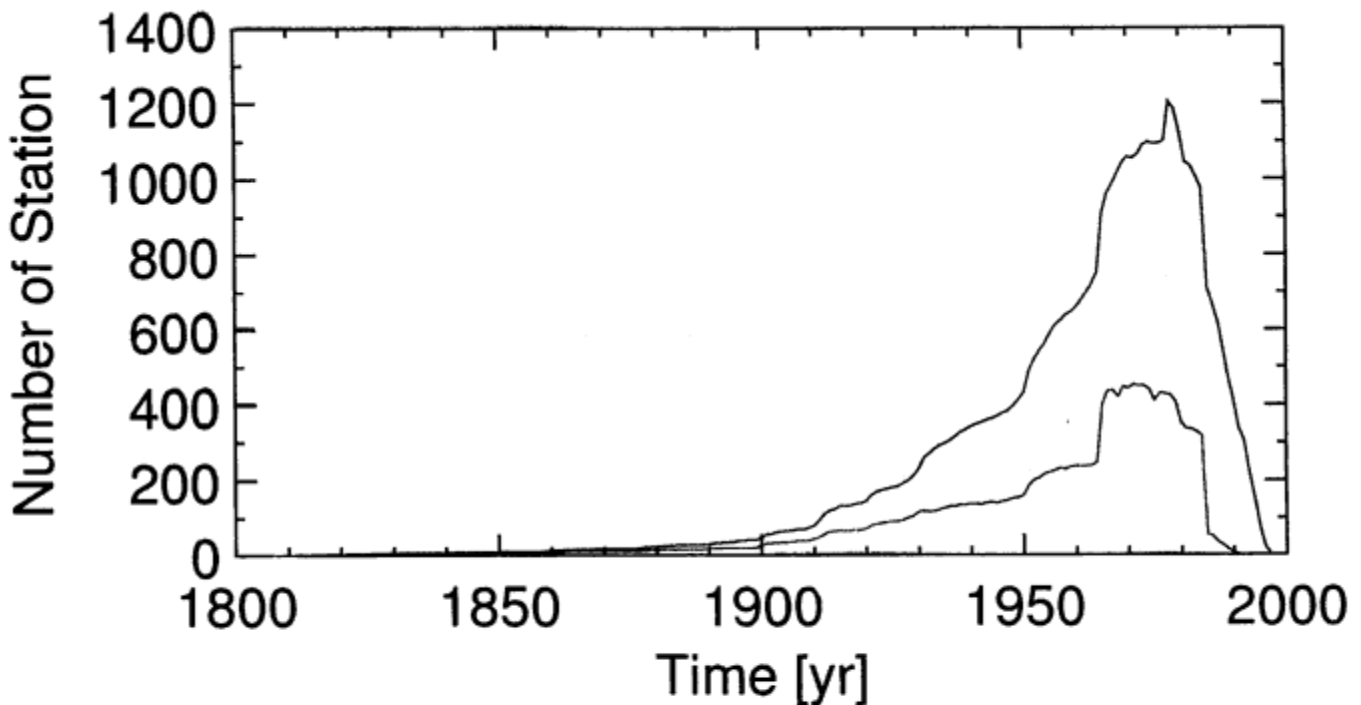


Figure 1. Time series of discharge gaging stations held by the WMO Global Runoff Center (top curve) a central repository for observations of continental runoff (Fekete et al. 1999) and that held within the University of New Hampshire RivDIS database (bottom curve, Vörösmarty et al., 1996a). Abandonment of stations, closure of previously open data sets, and delays in data processing conspire to limit the real-time value of these data sets.

1.3. Relationship to NASA Earth System Enterprise Science Objectives

The specific HYDRA-SAT mission questions, in turn, support a set of fundamental Earth Systems Science questions as articulated in NASA's New Vision of Earth Science (G. Asrar; Appendix A / NRA-98-OES-11):

- *Is the climate changing in ways we can understand and predict?*

- Can we understand and predict how terrestrial and marine ecosystems are changing?
- Can observations from new applications-oriented sensors be applied for the public good?

Better understanding of the state of the terrestrial water cycle is essential to each of these NASA ESE framework questions. The movement and storage of water at the earth's surface regulate a broad suite of Earth System Processes including atmosphere-land interactions, land-ocean coupling, terrestrial primary production, nutrient biogeochemistry and trace gas exchange .

Surface water systems, which can be monitored from space, are sensitive indicators of the variability of the land-surface branch of the global water cycle. For example, radar altimetry has demonstrated a link between climate variability in the Indian Ocean and inland lake level changes in East Africa and the Sudd (Birkett et al. 1999) (Figure 2). Links between El Niño

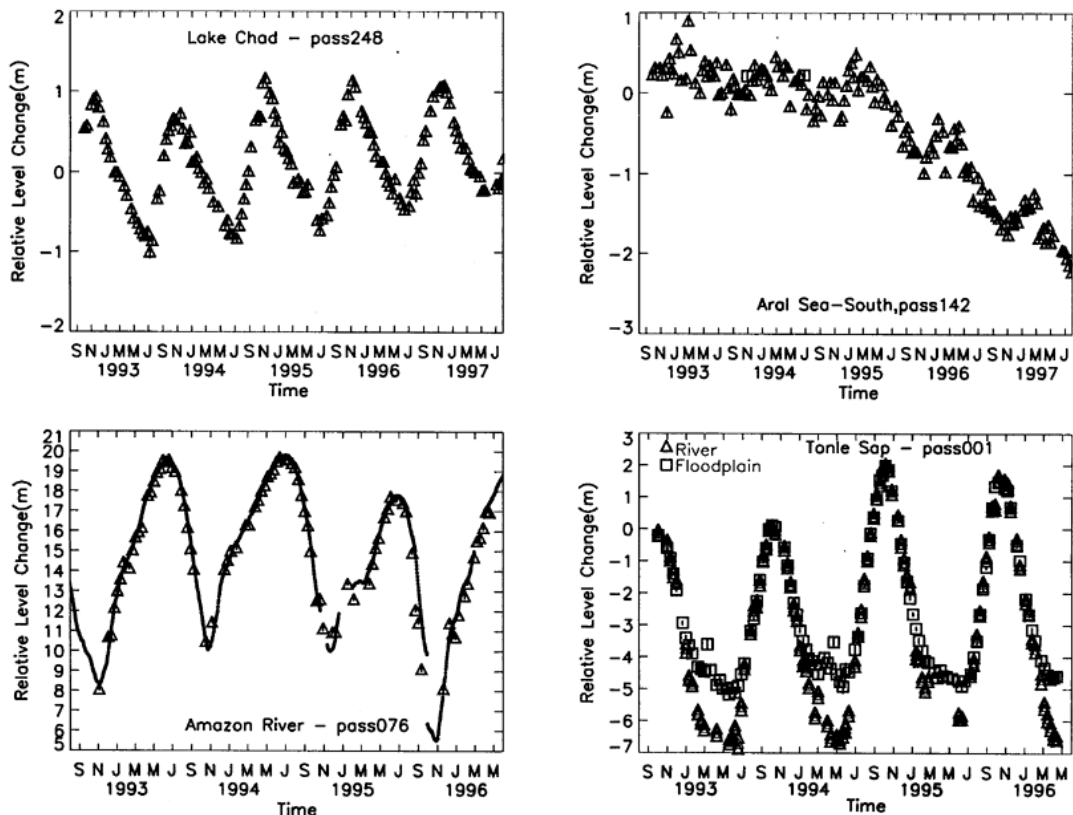


Figure 2. Time series of TOPEX/POSEIDON level changes for Lake Chad, the Southern Aral Sea, the Amazon River, and Tonle Sap. Note the comparison between the Amazon altimetry results and gauge data at Manacapuru (solid line). The altimeter is both able to monitor rivers and their floodplains (e.g. Tonle Sap). Note the rising levels of lake Chad, while the Aral Sea has decreased by 2.5m between 1993 and 1997.

climate anomalies and Amazonian river discharge are detectable using Nimbus-7 37-GHz passive microwave radiometer data (Vörösmarty et al. 1996b). The impact of such time variations extends beyond hydrology per se as net primary production of terrestrial ecosystems in Amazonia was found to be closely-correlated with inter-annual water status (Tian et al. 1998). The clear linkage of the continental land mass and the world's coastal zones through river transport is only now being systematically assessed (Seitzinger and Kroeze 1998, Ludwig and Probst 1998, Vörösmarty et al. 1997a,b,c, Oki et al. 1995) and would benefit directly from continental and global-scale monitoring of river discharge. Further, the capacity to monitor remotely the onset of drought and/or large floods has immediate and direct value to the public good, particularly in those parts of the world that are poorly monitored by surface networks.

2. MISSION BACKGROUND AND RATIONALE

2.1. Relevance to Earth Systems Science

River flow is a major component of the global water cycle, representing 40% of the long-term average export of moisture from the continents (Korzoun et al. 1978, Fekete et al. 1999). Streamflow has important implications for physics in the Earth's oceans, for example, the thermohaline circulation is closely linked to the freshwater balance of the Arctic Ocean basin, and in semi-closed inland seas such as the Mediterranean, circulation is strongly influenced by riverine inputs of freshwater. Rivers represent the primary source of freshwater for human use. Rivers play a key role in transport of dissolved and particulate materials within and from the continents. Humans are highly dependent on rivers for transportation, food, and waste processing. Freshwater lakes and artificial storage reservoirs account for more than 75% of the storage of freshwater over the global land surface, excepting Greenland and Antarctica (Shiklomanov and Sokolov 1983; Vörösmarty et al. 1997a). The storage, draining and filling of these water bodies are globally significant, imparting an influence on the apparent rise of sea level (Sahagian et al. 1994). Climate-induced variations in natural lake levels are also among the largest changes in continental water storage. The recent 1997 Indian Ocean event produced a sudden 1.7 m increase in the stage of Lake Victoria, likely representing the largest sub-annual volume increase for a single freshwater body, with a change predicted to persist for several decades (Birkett et al. 1999, Vörösmarty and Sahagian 1999).

Monitoring of the terrestrial water cycle has figured prominently in steering documents guiding the overall US Global Change Research Program (USGCRP), and individual agency contributions such as NASA's Earth Observing System and Mission to Planet Earth synthesis studies (National Research Council 1998, Subcommittee on Global Change Research 1995-97, Asrar and Greenstone 1995, NRC Space Studies Board 1995) and NOAA's Climate and Global Change Research Program. This emphasis is borne of a recognition that the water cycle is central to the Earth System and, further, that

global change may impart a hydrological signature that will be critical to detect and whose impacts are essential to understand.

A coherent system to monitor river flows, and changes in storage of freshwater in lakes and reservoirs, will be essential to any scientific assessment of global change. As compared to the other two primary freshwater fluxes, precipitation and evapotranspiration, river discharge is less susceptible to observational error because it is inherently an areally integrated flux which can be measured at clearly defined sites. Furthermore, river discharge integrates hydrologic behavior over complex landscapes, and therefore has a particularly important role in validating spatially-distributed climate, terrestrial ecosystem, and material transport models at continental and global scales. Lake and reservoir levels also provide an integrative measure of the state of inland waters (Birkett et al. 1998, Coe 1998).

2.2. Emerging Limits to Inland Water Monitoring

The capacity to remotely monitor the state of inland rivers, lakes, reservoirs, and wetlands globally is the central focus of this proposed mission. It could reasonably be argued that assembling a coherent picture of the state of the land-based hydrologic cycle is better addressed using information from traditional surface-based monitoring networks. However, there are critical technical, economic, and institutional impediments to assembling such systematic measurements. These include scarceness of surface observations stations in many remote areas, the inability to maintain reliable records due to political instability, and difficulties in acquiring data in near-real time. The latter problem is compounded by commercialization of hydrometeorological networks, and restrictions on release of data arising from the consideration of water as a strategic resource (e.g. see WMO-Global Runoff Data Center data policy 1.2 / 2.6). Even in regions traditionally endowed with rich hydrological monitoring networks a net loss of recording stations continues to take place. In the United States, for example, approximately 70-80 stations are being discontinued each year (Wahl et al., 1995, Hirsch 1999) while in the former Soviet Union approximately 30% of all stations have been lost since 1990 (pers. comm.; I. Shiklomanov, Director, State Hydrological Institute, St. Petersburg).

Even when data have been collected, delays in data reduction, quality control, and distribution often make this information of limited value to the user community. Both the WMO-Global Runoff Data Center (Grabs et al. 1996) and UNH-RivDIS global discharge data sets (Vörösmarty et al. 1996a) each show a peak coverage around 1980 and a precipitous decline thereafter (Figure 1). Further, even using the most complete global data set currently available (WMO-GRDC) we find that at best the discharge from less than 60% of land surface of the earth is monitored, and this peak was attained in the early 1980's (Fekete et al. 1999). Thus, in the context of growing concerns about climate change, when we need most an enhancement to our capacity to monitor changes in the land-

based hydrological cycle, traditional data sources are becoming less accessible. For applications at continental and global scales satellite-based sensors may offer the only feasible approach toward obtaining near real-time data for lake/river stage and river discharge.

2.3. Current Technology for Operational Monitoring

River discharge represents the throughput of water past a well-defined cross-section of channel or channel and inundated floodplain. Routine network observations of river discharge are based on river stage about some arbitrary datum, through well-established stage-discharge relationships or "rating curves".

At a given perpendicular cross-section of a river, the discharge, Q , at any instant is given by:

$$Q = VA = VWY, (1)$$

where V is average flow velocity, A is wetted cross-sectional area, W is water-surface width, and Y is average flow depth. Direct measurement of discharge is typically made by measuring velocity and area at various points along the cross-section of interest. Routine network observations of river discharge are typically made by periodic concurrent measurement of discharge and river level (stage) to establish the site-specific rating curve (stage-discharge relationship). Between discharge measurements, stage is monitored continuously and discharge is determined by reference to the rating curve.

The installation of stage-monitoring equipment, periodic measurements to extend and update the rating curve (typically 10 observations per year), and maintenance of the monitoring system are expensive, and are usually undertaken by government agencies. In the United States, the US Geological Survey operates some 7000 gages at a cost of about \$10,000 per gage per year (personal communication, W. Kirby, USGS, Reston VA). About 60% of these gages are equipped to telemeter real-time stage and discharge data using both the GOES and communication satellite systems that are then made available to the public on a provisional basis. The data are subsequently quality-checked and made available in paper, electronic, and CD form with a lag of one to two years, although near-real time data is now available on the World Wide Web. The typical relative precision of daily average flow values at well-monitored gaging stations is 10%. However, precisions of greater than 15% are not uncommon because of missing or distorted records due to scour and fill, flood damage, ice conditions, or vandalism and the difficulty of precise measurements at extreme flood flows and extreme low flows.

Routine observations of lake volume changes are made by periodic measurement of lake levels coupled with bathymetric information, typically a

"hypso-metric curve" relating stage to plan area variations. Reservoir volumes are also estimated from river inflows, evaporation, and impoundment releases as part of optimization schemes for flood management, water supply, hydroelectricity, and/or recreation. In the United States, most such observations are made on reservoirs that are actively managed by public agencies and/or private companies. Relative measurement precisions are generally similar to those for river discharge. Managed wetlands like the Everglades are also monitored in a similar way, specifically for the purpose of controlling water storage and flows for various end-uses.

3.0. BASELINE MISSION

3.1. Summary of Technical Strategy

The proposed mission will retrieve the stage of large rivers, the velocity of the river surface current (Scenario C only) as well as the along-track water body widths from which time-varying discharge and water volumes can be estimated. Alternative technology pathways are identified which could meet the science objectives presented above.

Scenario A – Established Radar Altimeter Technology with Doppler Processing.

This system would rely on mission-ready technologies that have a proven record of reliability on spaceborne satellite platforms. The primary sensor would be an enhanced radar altimetric system dedicated to the retrieval of surface water heights. It would also support a Doppler processing capability for the retrieval of river widths, thus requiring raw data storage and transmission capacity. A passive microwave radiometer would be included for determining atmospheric corrections. The satellite would also serve as a telemetry reception and transmission node, relaying standard stage information from cooperating, ground-based monitoring stations which would be later utilized for calibration purposes. Investigations of the T/P NASA Radar Altimeter (NRA) data set indicate that relatively simple hardware/software modifications to such a primary sensor would enhance the capability of this technology to be more globally effective for inland water monitoring. The Scenario A altimeter would thus be based on past/current radar altimeter missions (Seasat, Geosat, T/P, ERS), with a payload considered to be at a mature stage of mission-ready planning. Such a sensor with supporting hardware/software could thus be assembled as essentially a replica of existing technology at substantial savings.

Scenario B - Innovative Low Cost Radar Altimeter with Doppler Processing

This mission scenario is exploratory and has not yet been applied to inland water applications. Similarly to Scenario A, its aim is the derivation of water heights and along-track target widths. However, it will employ a large (~10m) nadir-viewing antenna for improved cross-track resolution and would omit the more complex peripherals (microwave radiometer, precise orbit requirements, dual-frequency operation) used in traditional altimeter systems. These will be replaced with a land-reference surface self-calibration technique, which with the radar antenna, would require several trade studies including proof-of-concept, on a series of airborne missions.

Scenario C – Doppler lidar for river surface velocity measurements

This mission would combine a radar altimeter with a Doppler lidar to obtain the two critical pieces of information needed to characterize the discharge from poorly monitored rivers around the globe. The lidar would be rather small (25 cm optics) and low wattage (<1 watt) which would be sufficient to enable velocity measurements within 10 meter footprints. The measurement of velocity would require a 30-45 degree off nadir viewing angle and would be able to sample within the full radius of regard (~ 500-1000km). The small diameter of the beam would permit penetration to the ground in excess of 50% of the time (day and night) including the 50% cloud porosity validated with the LITE.

3.2. Technical Heritage and Feasibility of Applying Existing Spaceborne Systems

Satellite radar altimeters have successfully retrieved echo information over inland water bodies. Early, preliminary studies explored Seasat data (Brooks, 1982, Olliver, 1987, Rapley et al., 1987, Au et al., 1989, Cudlip et al., 1990, Guzkowska et al., 1990) while Geosat and TOPEX/POSEIDON (T/P) data demonstrated the ability to monitor level changes in lakes and inland seas (Birkett, 1994, Morris and Gill, 1994a+b, Birkett, 1995, Dalton and Kite, 1995, Birkett and Kite, 1997, Cazenave et al., 1997, Ponchaud and Cazenave, 1998, Birkett et al., 1999). Unhindered by time of day, weather, vegetation or canopy cover, the technique has further been applied to a number of rivers, wetlands and floodplains in several test-case studies (Koblinsky et al., 1993, Birkett, 1998). Results demonstrate how sub-monthly, seasonal, and interannual variations in surface water height can be monitored (Figure 2).

The primary priorities of current (T/P, ERS-2) and future (Jason-1, ENVISAT) radar altimeter missions however, lie with ocean or ice studies. The latter is also a goal of laser altimeters, but the lack of specific repeat orbits and the problem of cloud contamination inhibits their frequent, global application to river, lake, and wetland monitoring. In addition, hardware/software and standard data set configurations of radar altimeters are not optimized for retrieval of surface heights

over inland waters. The cloud contamination issue, however, is much less a problem for coherent Doppler lidar designed to measure target velocities.

3.3. Technical Requirements to Support Science Goals

The primary science requirements of a surface water monitoring mission dictate the following technical constraints:

- (a) River, lake, reservoir and wetland surface height data should be globally retrievable (spanning at least ± 65 deg latitude) for targets ~ 250 m wide (rivers) or ~ 100 km² in surface area (others) and with an accuracy of 5cm rms;*
- (b) River widths should be estimated to within 10m accuracy;*
- (c) River surface velocity should be measured to within 20 cm/s RMS accuracy*
- (d) The maximum overpass repeat should be 3-7 days;*
- (e) River crossings should be repeatable from orbit to orbit to within ± 125 m across track; and,*
- (f) Useful preliminary data must be processed and made publicly available in near-real time.*

Certainly, the excellent performance capability of T/P over inland waters (both ocean-like returns from lakes and inland seas and highly specular echoes over rivers and wetlands), together with a repeat-orbit frequency of only 10 days and excellent knowledge of satellite orbit, have led to attained accuracy of 3-4cm rms for lakes and >10 cm rms for rivers. However, with an along-track sampling rate of 10Hz (10 echoes every 5.8km in the along-track direction), a footprint of several kilometers, and the complex effects of topography, the application is limited to large targets (≈ 300 km² lakes, >0.5 km width rivers), and only those that are located along a ground-track, the positioning of which is chosen by the ocean community. In addition, full resolution T/P data sets are only available 1-2months after satellite overpass, and fast-delivery data (?2days delay) is available at low resolution for ocean surfaces only. The ERS instruments also potentially offer inland water data to ± 82 degrees latitude, but the greater spatial coverage (i.e. increased number of target hits) is offset by poor temporal resolution (35days).

No currently operating or currently proposed altimeter meets all of the inland water requirements. One possibility of Scenario A is to collaborate with the ocean/ice communities to reconfigure their current sensors and data processing systems over land surfaces to maximize the use of satellite operating time.

Scoping studies may well reveal simple trade-offs and synergies between the ocean/ice and inland water communities.

3.4. HYDRA-SAT Mission Concept (Scenario A)

3.4.1. Overall Mission Specifications -- Scenario A

Configuration of the HYDRA-SAT sensors and satellite platform system is given in Table 1. The instrument is a two frequency (Ku, C) satellite radar altimeter (nadir-viewing/pulse-limited operation) with a capability of monitoring both specular and non-specular inland water surfaces. Consideration would be given both to the production of final data sets with along-track sampling intervals of >20Hz, and to the storage of raw-data (at the Pulse Repetition Rate) to allow for Doppler post-processing of echoes for river width retrievals. Day/night, all-weather, and penetration through vegetation/canopy to underlying inundation regions would be ensured. Near-real time (one-day delay) and standard (1-month delay) data sets would be delivered for product analysis. The satellite platform would include a 3-frequency microwave radiometer for determination of atmospheric effects over large lakes and reservoirs, an attitude control unit, and GPS/SLR navigational systems.

TABLE 1. Summary of Technical Specification, HYDRA-SAT Scenario A

The following specifications serve as a guideline. The final selection of certain parameters will be based on the technology and science investigations outlined in Section 5.

Transmit Central Frequency:	13.6GHz (Ku band), 5.3GHz (C band)
Pulse Width:	100ms
Bandwidth:	300-600MHz
Pulse Repetition Frequency:	4-7kHz (Ku), 1.2kHz (C)
Antenna Diameter:	1-2m parabola
Gain:	44dB (Ku), 35dB (C)
Waveform sample:	128 per channel
Transmit Power:	5W
Range Resolution:	<0.5m
Vertical Height Accuracy:	5 cm
Final Height Sampling Rate:	>20Hz

Along-Track Spatial Resolution:	1-5m
Platform Height:	800-1300km
Orbital inclination:	65deg
Orbital Cross-Track Drift :	<±125m
Telemetry Rate:	1228 byte frame, 10kb/s

A number of simple platform/software/hardware modifications to existing altimeter systems would allow for an enhanced system:

(a) Orbital selection and control to permit extended coverage to at least ±65degrees latitude, to optimize the location of inland water targets and validation sites, to achieve a temporal resolution of =3-7days, and to attain a cross-track drift of ±125m of a nominal reference track;

(b) Modifications to existing tracking systems to enable rapid surface lock in variable terrain conditions, and to sustain stability over the target surface;

(c) Modifications to pulse duration and frequency bandwidth with relevance to footprint size and attainable range precision;

(d) A minimum along-track sampling of 20Hz to allow for the detection of smaller targets; and,

(e) The retention of fast-delivery land data for near-real time products.

3.4.2. Technology -- Scenario A

The system would consist of a nadir-looking radar altimeter system operating at Ku and C band wavelengths, with synthetic aperture (Doppler beam sharpening) post-processing and additional telemetry capacity for relaying ground-based gage information. The altimeter proposed here has three key attributes differentiating it from traditional altimetry systems:

- The radar instrument would be an enhanced altimetric system with modified telemetry/sampling rates, fast tracking constants and smaller ground footprint for increased performance of inland water targets with regard to global coverage and achievable target size. Digital terrain models (e.g. NIMA DTED-I or SRTM global data set) and the application of preset tracking would contribute towards maximum data acquisition. Improvements to range precision, knowledge of satellite orbit and atmospheric corrections would ensure a best-achievable overall surface water-height accuracy.

- Storage and subsequent downlink of the raw radar data (not coherently averaged in existing altimetry systems) would allow the application of a synthetic aperture technique which coherently analyzes the Doppler signals. This would allow a form of "quasi-imager" to take advantage of the specular nature of river echoes, enabling an along-track river "width" (inundation extent) to be derived. Full data interpretation and analysis would be performed via post-processing. Theoretically, the expected achievable resolution is approximately half the antenna dimension (~1-5 m).
- Additional antenna/telemetry capability for the relaying of stage/discharge information from conventional ground gages to selected ground-processing sites. Collection of this additional data would serve as validation of the derived altimetric height time series and application of the stage/discharge rating equations.

Prior to global analysis, full assessment of (a) instrument performance by NASA calibration/validation teams, (b) orbital precision, (c) data validation by ground-processing teams, and (d) analysis of resulting inland water data at target study sites must be completed. Validation studies will require access to the telemetered gage data, surveys recording inundation extent via aircraft fly-overs, and access to high resolution radar imagery.

3.5. HYDRA-SAT Mission Concept (Scenario B)

3.5.1. Overall Mission Specifications -- Scenario B

The instrument concept for Scenario B is a nadir viewing, high-bandwidth, single frequency radar altimeter with synthetic aperture processing (Doppler beam sharpening) being employed to obtain the along-track resolution, and a large antenna to obtain the cross-track resolution. The science technical objectives are as for Scenario A. The instrument would not be intended to operate over oceans due to data handling constraints, however the possibility of dual operation to serve the ocean communities would be the topic of a scoping study (Section 5.1). The technical specifications for Scenario B are given in Table 2.

The hardware would consist of a standard deployable antenna with modified rectangular feed to partially illuminate the reflector. The along-track system resolution would be equal to half the antenna length. The cross-track resolution would be determined by the altimeter cross-track beamwidth. Thus a large antenna, 10m for Ku-band or 5m for Ka band, is required. Such antennas are technology feasible, but have not yet been demonstrated in a spaceborne mission.

As a cost-effective measure, the determination of accurate surface water heights based on precise knowledge of both satellite (orbit) and atmospheric corrections

by associated additional hardware, could be replaced by a land reference surface technique. This technique assumes the *a priori* identification of suitable land surfaces along each satellite overpass and its merits and limitations would need to be explored in a scoping study (Section 5.1). In addition, the replacement of dynamic range tracking by the use of a preset tracker (based on GPS, or by the use of SRTM or NIMA DTED-I digital elevation models) which can be fine-tuned during the mission, would also be considered.

Preliminary details of the proposed Scenario B instrument, including a discussion on the choice of Ku/Ka band and a description of the land reference surface technique, can be found in Appendix A.

TABLE 2. Summary of Technical Specification, HYDRA-SAT Scenario B

The following specifications serve as a guideline. The final selection of certain parameters will be based on the technology and science investigations outlined in Section 5.

Satellite Orbit:	400km
Transmit Frequency:	13.6GHz (Ku) or 35GHz (Ka)
Antenna width:	10m
PRF:	7kHz
Pulse width:	50ms
Bandwidth:	400Mhz
Transmit Power:	5W
Cross-track drift:	±125m

3.5.2. Technology -- Scenario B

The technology strategy for derivation of water body height and along-track widths is basically the same as for mission Scenario A. However, for Scenario B, full de-ramp compression will be used on board to reduce the data bandwidth and perform range compression (as in standard altimeter systems), but the echoes will not be incoherently averaged prior to telemetry. Instead the data would be downlinked to the ground where full post-processing will commence. The along-track resolution (target width) would be achieved by using synthetic aperture radar (SAR) processing. Height accuracy would be obtained by

standard waveform fitting, with the additional advantage of a reduction in processing requirements for specular river and wetland echoes.

Although this technology has been previously proven, it has not been applied to inland water targets to date. A number of scoping studies are therefore required including exploration of existing raw data collected by the ERS-1 and ERS-2 altimeter data segments, and hardware testing using aircraft fly-overs (Section 5.1).

3.6 HYDRA-SAT Mission Concept (Scenario C)

3.6.1 Rationale for a Hydro-lidar

The observation of the river surface current velocity is argued to be key in developing a capability to measure the fresh water discharge of rivers over the entire globe. Combined with river surface elevations at various stages throughout the year, a profile of discharge and river stage/surface current could be constructed without the need for extensive ground instrumentation and its maintenance. Within this context, surface velocity measurements (which would be used to estimate cross-sectional average velocity via standard engineering hydraulic assumptions) are not necessary at every overpass at which a (radar altimeter) stage measurement would be taken. It is only necessary to estimate cross-sectional average velocity (hence discharge, when combined with cross-sectional area information derivable from the Scenario A or B radar altimeter) at sufficient times to allow construction of a discharge rating curve (relationship between stage and discharge). For comparison purposes, at its (in situ) river discharge stations, which measure stage continuously, the U.S. Geological Survey typically takes discharge measurements 6-8 times per year. These discharge measurements form the basis for the rating curve, which is used to produce (continuous) estimates of discharge.

With a scannable beam, a lidar could perform several transects of a river whenever the river was within the satellite's view (~ 500 – 1000 km lateral distance from satellite ground track). The general strategy would be to have a detailed digital map of all the rivers to be targeted loaded into the on-board computer. The lidar scanner would be programmed to position the beam to achieve a ground sampling pattern that included 3-5 shots on each river bank and several 10s of shots/km) on the river surface. The bank shots would provide good zero velocity checks as well as height calibration checks. Simulations by Emmitt (personal communication) suggest that for rivers such as the Mississippi (between the northern boarder of Arkansas and the Gulf of Mexico on the order of 100 transects could be obtained per overpass.

Lasers using direct detection have been flown in space (SLA, LITE) and are being developed for near future missions such as Picasso, VCL and Icesat. The applications involve cloud/aerosol detection and ranging to the earth's surface.

To measure river surface speeds might require rather large optics and transmitted power if direct detection methods are used. Although cloud cover usually limits optical systems, airborne and space-based experiments have shown that lidar beams penetrate cloudy views 40-60% of the time, which makes a 50% signal recovery target a conservative estimate.

Here we propose to investigate the merits of coherent Doppler detection, which is fundamentally more photon efficient than direct detection. Coherent detection has been used for several decades to measure the tropospheric winds with ground based and airborne lidars. In the case of airborne systems, the surface returns have been used as points of reference, not as potentially useful data. The ability of getting a good velocity measurement per individual shot is particularly attractive for assessing horizontal representativeness of observations. It should be noted that an instrument such as that described below could also provide measurements of ocean currents, lake surface heights, and winds in the lower troposphere and near clouds.

3.6.2 Overall Mission Instrument Concept Specifications – Scenario C

The instrument concept for Scenario C is a nadir viewing, coherent Doppler lidar that would measure the velocity of river surface currents as well as (optionally) the height of the surface of the water body. The illumination spot at the surface would be order 10-20 meters, with the potential of making velocity measurements at each shot location. Table 3 summarizes the notional instrument for achieving the objectives stated in Section 1.1 with respect to river surface velocity.

TABLE 3 Summary of technical specifications of a notional space-based "Hydro" lidar

Satellite Orbit:	400-500km (or 833km NPOESS)
Laser wavelength:	1.5 – 2.0 microns (eyesafe)
Telescope diameter:	< 25 cm
Energy per pulse:	10 – 100 mJ
PRF:	10 – 100 Hz
Transmit power:	< 1 watt
Illuminated spot diameter:	10-20 m
Velocity resolution:	< 10 cm/s with shot averaging
Height resolution:	TBD (goal of 5 – 10 cm)

Nadir scan angle:	30-45 degrees
Scanning strategy:	Step stare

The HYDRA-SAT Doppler lidar instrument would be based upon the technology developed by NASA to measure tropospheric winds from a space-based platform. The notional system would consist of six major components:

- A laser transceiver which includes an LO,MO and SO.
- A beam expander and a scannable wedge (30 degree)
- A detector/signal digitizer (may involve signal splitting for separate range and velocity data processing)
- A CDMS for instrument control and data acquisition
- A GPS/INS for coarse position and attitude knowledge
- A software package that uses the lidar surface returns for fine PVT/RPY knowledge.

3.6.3 Technology feasibility study and demonstration

The idea of using a space-based lidar to measure stream flow is new and needs to be carefully studied. A feasibility study should be performed (~ 3-6 months) involving hydrologists, laser technologists and space-based instrument engineers. If the notional concept is sound, then a ground-based demonstration should be conducted using hardware that may already exist in the NASA laboratories. Such a demo could be conducted from a bridge near an existing (USGS) gauging station. This demonstration would serve to define how a space-based prototype system would be developed and evaluated (airborne).

3.7. Data Management

The proposed data management and processing plan will be similar under both Scenario A and B, with an emphasis on near-real time capability. Scenario A employs proven satellite-based technologies with a well-established heritage of data processing procedures (e.g. T/P, ERS-1, ERS-2). Tests of a data processing system must necessarily become a part of the proof-of-concept activities for Scenario B. The same is true for Scenario C.

3.7.1. Provision of Near-real Time and Standard Products

Specific altimetry/velocimetry data products will be:

Level 0: Data sets distributed by Data Processing Centers

Level 1: Preliminary data products produced in near real time

1a - surface water height variations

1b – surface water velocity

1c - along-track target widths

1d - river discharge data

Level 2: Updated, error-checked data products

2a - inland water height variations

2b - river discharge

Level 3: Derived lake, reservoir, and wetland volume change

Level 0,1,2,3 products should be made available to the user community through a dedicated data system.

Level 0 and 1 (raw data and preliminary products) will be ready for distribution on a near real-time (1-2 day delay) basis. Level 2 products, with higher quality controls, will be made available within an approximate 1 month delay. Level 3 products will be made available according to the availability of supporting global radar imagery data sets.

During the lifetime of the mission the Level 0 data sets may pass through several upgraded sequences by the ground processing teams. Level 2 products will therefore be recomputed for each upgrade of the Level 0 data set

A contemporary, near real-time state of inland waters would require several dedicated mission-related teams: orbital, instrument-related, ground processing, calibration/ validation, and inland water data processing teams. The first four teams would be responsible for orbital and Level 0 data set quality. Level 1-3 product quality and validation would be performed by the dedicated inland water team. Validation would be achieved through ancillary land-based information, such as from hydrometeorological services and hydroelectric operators.

3.7.2. Data Set and Data Product Processing Sequences

The altimetric data set (Level 0) processing sequence described below is based on current procedures whereby flight control centers, data downlink facilities (such as Wallops Flight Facility), and data processing facilities (such as PO.DAAC) are required. There will be four primary data sets delivered for which the processing centers will be responsible, and from which the data products given in Section 3.6.1 will be derived.

TD	Telemetered Data
SDR	Sensor Data Record
FD	Fast Delivery Data set
GDR	Geophysical Data Record

Telemetered data (TD) will be collected via data downlinks, and later transmitted to the data processing centers for routine processing of the raw radar data. Recordings of the microwave echoes will be formed into engineering units or sensor data records (SDR). Preliminary orbital (5cm rms) and geophysical data will be collated with altimetric information from the TD data to produce a high resolution (>20Hz) Fast Delivery (FD) data set which should be made available within one day of satellite overpass and stored at a designated FTP accessible site. Updated geophysical and range corrections, and more precise orbital information will be later calculated and incorporated into geophysical data records (GDR). Both GDR and SDR data sets would be distributed via standard CD-ROM or exabyte format within one month of satellite overpass.

The production of data products (Levels 1 to 3) from the above data sets will be done by a designated inland water analysis team. The following serves as a preliminary guideline:

- (1) Initial identification (in terms of quantity, geographical location and timing) of satellite overpasses over target areas;
- (2) Data ingestion from TD, FD,GDR and SDR data sets;
- (3) Altimetric and geographical parameter extraction and construction. Parameters would include, time/day, latitude/longitude, corrected altimetric height, standard deviation of heights, radar backscatter, instrument operation modes, quality flags and raw radar echoes;
- (4) Application of repeat track techniques to deduce initial surface water height variations from the FD data set (Level 1a product);
- (5) Application of near real time Doppler data to deduce river widths from the TD/SDR data set (Level 1b product);
- (6) From (4) and (5) the deduction of preliminary river discharge (Level 1c product);

(7) Upgrade of Level 1a+b products using SDR and GDR data sets (Level 2a+b products);

(8) Estimation of lake/wetland volume change (Level 3 product) based on modeled or observed hypsometric relationships and/or imagery data.

The construction of altimetric height will be based on:

$$Height = [Orbit - (Range_{CORR})] + T_L + T_P + T_E + Slope \quad (2a)$$

where,

$$Range_{CORR} = Range + Atmos_{WET} + Atmos_{DRY} + Atmos_{IONO} + embias + swh/att + Retrack, \quad (2b)$$

Orbit denotes the satellite orbit altitude, *Range* the altimetric distance between the altimeter and the surface. *Atmos* denotes atmospheric (wet and dry tropospheric, ionospheric) corrections and *T*, tidal corrections (L=lake, P=pole, E=earth tide). For rivers and wetlands, the electromagnetic bias and significant waveheight/altitude corrections, *embias* and *swh/att*, are not applicable (but are so for lakes), and model-derived atmospheric corrections are utilized in place of the instrument-derived *Atmos_{WET}* and *Atmos_{IONO}*. *Slope* is a correction to account for topographic gradients, and both *Slope* and Lake Tide, *TL*, may have to be estimated or at least their influences calculated, from external sources for each target region. The *Retrack* correction associated with the location of the true mean surface from the radar echo, will be derived from analysis of the SDR data set. (See Birkett (1995,1998) for discussions of height accuracy and errors).

For lake surfaces, height accuracy will be dominated by knowledge of the satellite orbit, and by *Atmos_{WET}* if the lake is too small for the application of the instrument-derived value of the latter. The latter will also affect the accuracy of height values over rivers and wetlands, but due to their specular response, the determination of the *Range* value will also be a strong factor. The *Range* precision can be improved by averaging a number of along-track echo-derived height values across the region of interest. For the Scenario B instrument, land reference surface techniques may well preclude the requirement for a precise orbit value and knowledge of the atmospheric corrections.

3.7.3. Telemetered Information

HYDRA-SAT would maintain a telemetry receiver and re-broadcast system to relay data from ground-based stations. Collaborating agencies with time-varying stage data collected from automated data transmission platforms deployed in the field may provide additional calibration and validation targets for the altimeter and

Doppler retrievals. The system may also be able to relay additional information such as water temperatures. This would require standard transmission protocols for data upload to HYDRA-SAT, onboard storage, and satellite download to the central processing facility. The protocols could follow already established procedures used by the global weather community (e.g. as for the Global Telecommunications System).

3.7.4. Ancillary Data

For lake and wetland studies it would be highly desirable to have additional imaging radar data to chart the spatial variations in plan area of these water bodies. This information in tandem with stage heights will permit an assessment of water volume changes over time. However, such data would not be necessary in real time – it is only necessary that stage and surface area extent be concurrently observed at some time during the mission.

For river discharge estimation where ground-measured river cross-sectional information is lacking, ancillary data from imaging radar, maps, and digital elevation models (DEMs) would be necessary to guide the rectification of remotely-sensed, pathwise water-surface width data (determined from the Doppler processed radar data) to a water-surface width perpendicular to river flow (see Eqn. 1). On large rivers, imaging radar information could be derived from the imaging L-band SAR of the cryospheric monitoring portion of the overall Land Surface Hydrology Mission. As discussed later, independent land-elevation information derived from maps, DEMs, or high-resolution land-surface altimetry such as provided by LIDAR and/or SRTM would also be used to provide information about river slopes and thereby estimated discharge.

3.7.5. Data Archiving and Distribution

The various Level 0, 1, 2, and 3 products will be stored and distributed using standard FTP and WWW-based protocols on one or more participating nodes which could include GSFC, NASA DAACs and NASA ESIPs. An ESIP federated hydrology group could be an excellent repository for this data set. Level 1 information would be archived in near-real time with warning flags prior to error-checking. A data stress test will need to be performed with full processing from Level 0 through Level 3.

The algorithms described in Sections 3.4 and 3.5 would yield the altimetric height and width information. These will be further processed to develop a coherent data base of high level geophysical products for the user community. These data would apply to all of the target sites consisting of rivers, lakes, reservoirs, and wetlands. The information set would include in addition to the derived water heights, surface velocities and change in stage an estimated width and area, predicted discharge (for rivers), and volume changes (for all targets), as summarized in Table 4.

TABLE 4. Primary HYDRA-SAT Data Products

The targeted set of geophysical data products generated by the HYDRA-SAT mission are given below.

<u>Target Location</u>	<u>Number of Sites</u>	<u>Products</u>	<u>Sensor</u>	<u>Units</u>	<u>Accuracy</u>
Lakes/reservoirs^a	1400	Stage	Altimeter	m	± 0.05m
		Area	Imager^b	km²	± 5%
		Δ Volume	Computed	km³	± 5%
Wetlands	1000	Stage	Altimeter	m	± 0.05m
		Area	Imager^b	km²	± 5%
		Δ Volume	Computed	km³	± 5%
Rivers^a	2000	Stage	Altimeter	m	± 0.05m
		Width	D.P.^c	m	± 1-5 m
		Velocity	lidar^d	m/s	± 0.20 m/s
		Discharge	Computed	m³ sec⁻¹	± 10%

^a Based on 100 km² minimum area; minimum eligible river width for altimetric stage retrievals is 0.25 km.

^b Radar imager such as from proposed cryospheric mission, ERS-2, Jason, ENVISAT.

^c D.P. = along-track Doppler processing.

^d Doppler lidar

4. SCIENCE STRATEGY

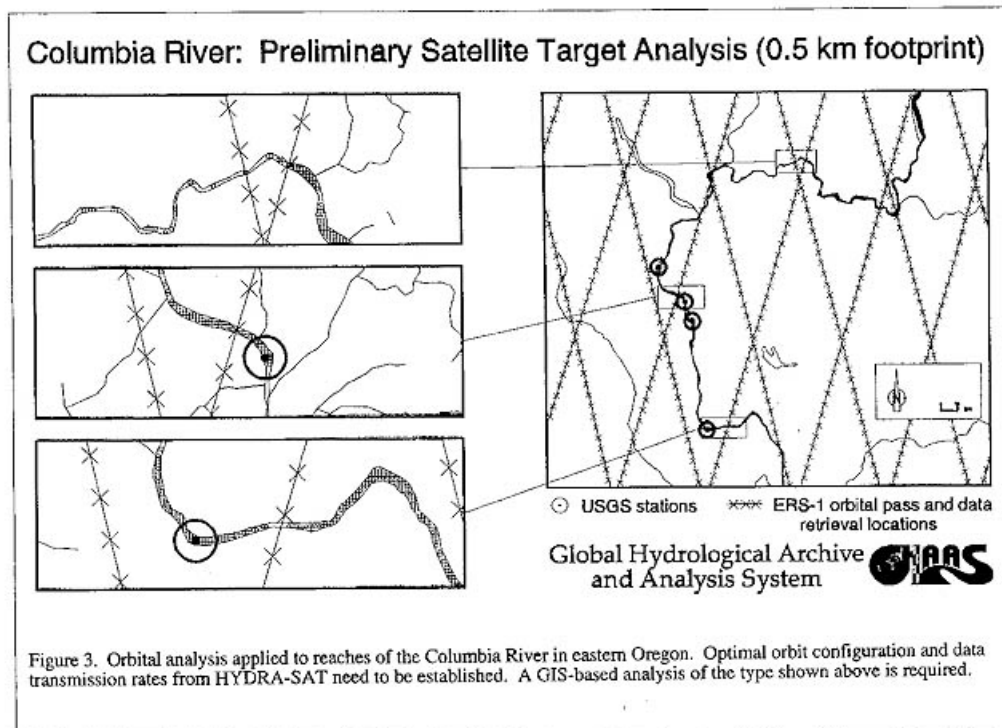
HYDRA-SAT employs radar altimetry which has the distinct advantage of securing observations under all weather conditions and (Scenario C only) Doppler lidar which can provide accurate river flow velocities under many weather conditions. The vertical and horizontal resolution requirements of the satellite instrumentation for the proposed mission was discussed in Section 3.3. These specifications determine the ultimate number and size of rivers and lakes for which stage and discharge can be usefully observed remotely and the ultimate limit of precision in the determination of stage, discharge, and lake volume changes from the Scenario A, B and C missions.

4.1. River Discharge

In principle, river discharge can be inferred from: (1) stage-discharge rating curves, which are most accurate for in-bank (non-flood) flows in single-thread (non-braided) rivers; or (2) width-discharge rating curves, which are most useful for flooding rivers and for braided rivers at all stages. Thus, within the limits imposed by the targeted vertical and horizontal resolutions, HYDRA-SAT estimates of discharge can potentially be made via the following strategies.

4.1.1. Identification of Candidate Sites

The altimeter footprint will impose a practical limit on the usefulness of stage and width retrievals in large rivers, lakes, and wetlands. An orbital analysis will need to be performed to optimize the set of candidate sites. The approach involves superimposition of various orbital and along-track sampling rate configurations onto fine-scale GIS mapping of river courses, lakes, and wetlands. A search for suitable river widths would be necessary for the inference of discharge. Knowledge of the position of nearby gaging stations would also be important to provide suitable calibration and validation targets for the satellite estimates of both stage and discharge. Analysis of alternative scenarios varying the orbits, sensor resolution, along-track sampling rates will be necessary (**Figure 3**). It is also important that tests be performed on real station time series to explore the temporal sampling and revisit times of the satellite necessary to optimize useful estimation of discharge (**Figure 4**). Sensor rms errors on stage (and velocity, under Scenario C) also need to be analyzed, in particular to estimate *a priori* the penalty in discharge accuracy associated with different accuracies in remotely-sensed stage.



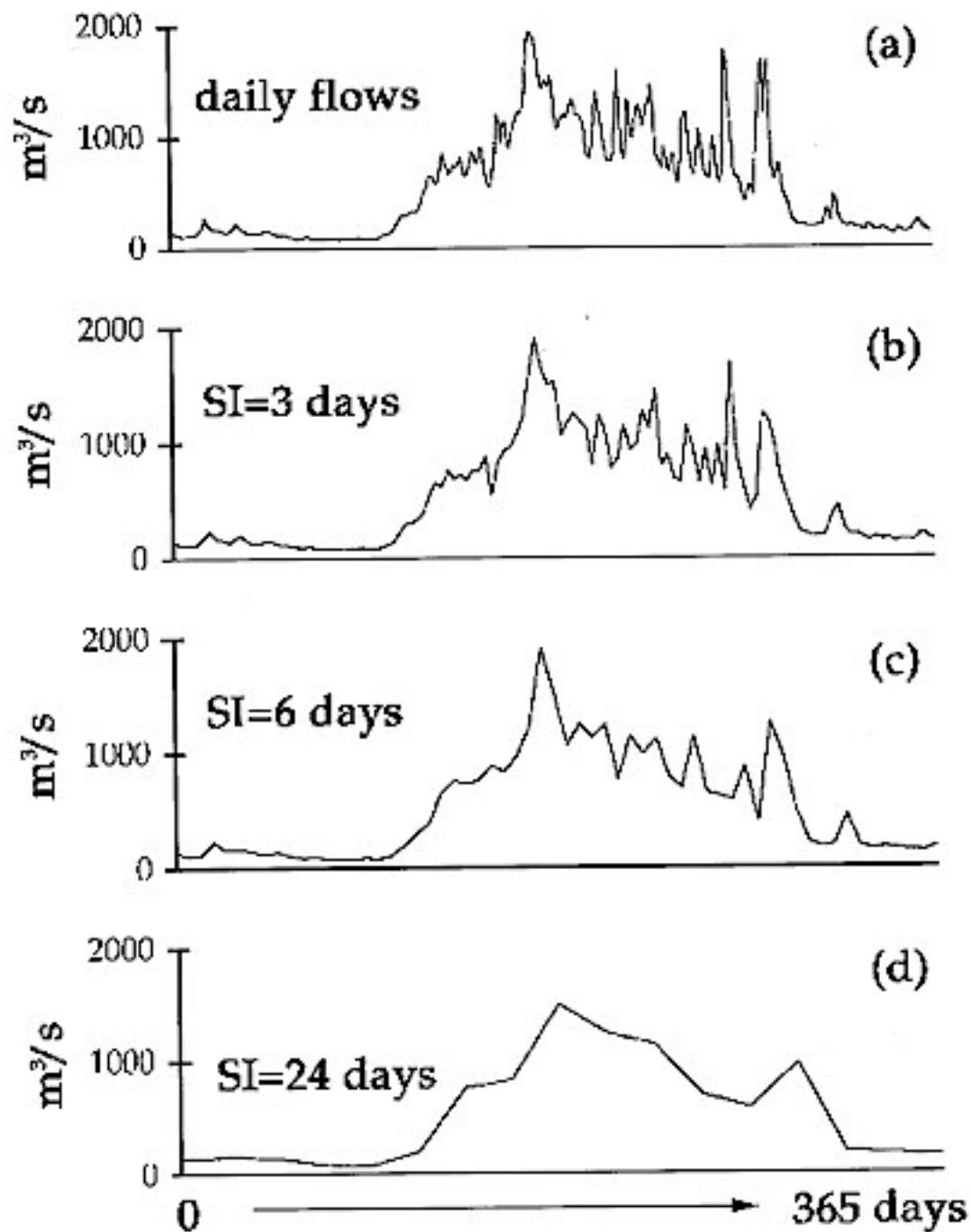


Figure 4. Impact of alternative temporal sampling strategies of daily discharge. An optimal repeat cycle of HYDRA-SAT will need to be determined. It is anticipated that a 7-10 day re-visit time would be sufficient for large rivers. (From: Smith et al. 1997).

HYDRA-SAT will carry transceivers equipped to access and relay stage information from operational stream gages equipped for telemetering. At present, 64% of gaging stations maintained by the US Geological Survey are so equipped (Wahl et al., 1995, Hirsch 1999), but globally the percentage is much smaller. Additional calibration and validation targets and may also provide boundary conditions for interpolated stage and discharge estimates on rivers. Such site data could be obtained from WMO-W/HYCOS, Environment Canada, and other such monitoring agencies which maintain telemetered gaging stations.

4.1.3. Use of Existing or constructed Stage Rating Curves

This approach couples HYDRA-SAT altimetric measurement of stage with rating curves (Q versus stage) established by ground measurement at existing or discontinued gaging stations that are usefully close to ground-track cross-sections. This approach will provide the most accurate discharge estimates, and has been the basis for most published satellite-based discharge estimates (Koblinsky et al. 1993; Smith et al. 1996; Smith 1997). However, in most cases, orbital crossings of rivers will not coincide with surface sites, so only a small number of sites globally are likely to fall within this category. It is therefore necessary to develop interpolation techniques based on explicit hydrodynamic models or statistical approaches to determine discharge at orbital crossings.

4.1.4. Development of Rating Curves from HYDRA-SAT Observations

The development of depth- and width- rating curves requires specific information about the geometry of measurement cross-sections and a means of estimating velocity (Eqn. 1). Under Scenarios A and B, HYDRA-SAT will make repeated passes over the same river cross-sections with a precision of a few hundred meters, measuring elevation, and pathwise water-surface width each time. This width-elevation data can be used to impute channel cross-section geometry. As the satellite track will not in general be perpendicular to the channel, the width observations will have to be resolved to the perpendicular using independent channel-orientation information

derived from maps or high-resolution land-surface altimetry such as provided by LIDAR and/or SRTM. This information can be supplemented by existing map and DEM data, other satellite altimetry, and by generalized channel cross-section geometry relations developed from open water hydraulics techniques.

Where existing rating curves are unavailable, this width-elevation data can be used to estimate a channel cross-section geometry. The following approach may be followed:

(1) Assume a channel cross-section shape - e.g., parabolic, which is often assumed for natural channels. The equation for such a section is given by:

$$(W/2)^2 = 4*K*(Z - Z_0) \quad (3)$$

$$Z = Z_0 + W^2/(16*K) \quad (4)$$

where K is a constant and Z₀ is the elevation of the deepest point of the channel (center).

(2) Hydra-Sat will make successive observations of W/cos (q) and Z, where q is the angle between the ground path and the perpendicular to the channel. q can be determined by reference to maps and ancillary information such as DEMs, LIDAR or other satellite observations of land surface elevations. Thus we have concurrent values of W and Z.

(3) Using these concurrent values, we can regress Z vs W² to find least-squares estimates of Z₀ and K.

(4) The maximum channel depth Y_{max} = Z - Z₀. For a parabolic channel, the average depth, Y = 2*Y_{max}/3. Thus we now have estimates of Y and W for each observation.

(5) To find Q, we turn to the empirical equation developed by Dingman and Sharma (1997), which gives Q as a function of cross-sectional area (A= W*Y), hydraulic radius (essentially = Y), and water-surface slope. Lacking direct observations of water-surface slope, we would use estimates of channel/floodplain slope in the equation. Such slope estimates can be derived from the same ancillary sources mentioned in Step 2.

Generalized channel cross-section geometry relations developed from the hydraulics literature (e.g., Henderson 1966) may prove superior to standard geometric shapes such as the parabola, but the same basic approach can be used to fit cross-section form to successive observations of elevation and width. River types (e.g., according to the Rosgen's [1996] classification scheme) can be identified on the basis of river planform and topography and used as a further guide the construction of cross sections where direct ground measurements are unavailable.

Additional information to guide the construction of cross sections can be obtained from generalized relationships between bankfull discharge and various channel

features that can be detected from HYDRO-SAT observations and ancillary information. There are at least 4 possible approaches that can be exploited:

(i) A number of studies have established strong relations between bankfull widths and bankfull discharges (e.g. Dury 1976; Williams 1978; Bray 1979; Dingman and Palaia in press), and between bankfull discharges and drainage areas. As drainage area can readily be determined for any site, it should be possible to estimate bankfull width and discharge for most regions. This provides a starting point for estimating the channel geometry using generalized hydraulic geometry, and gives an estimate of one point on the width and depth rating curves.

(ii) Smith et al. (1996) used width-discharge relations and observations of stream sinuosity to estimate discharge in two braided streams in Alaska. They estimated that their approach can be used to estimate discharge to within a factor of 2 in the absence of ground measurements.

(iii) Osterkamp et al. (1983) showed that bankfull width/depth ratios of alluvial channels are predictably related to mean discharge. Since estimates of mean discharge are generally available from basic climatic water-balance information, these relations can be used to help construct synthetic channel cross-sections.

(iv) For meandering streams, meander wavelength is closely correlated with bankfull width and discharge (e.g. Dury 1976). Thus, measurements of meander characteristics derived from maps and other imagery can be used to provide a starting point for estimating the channel geometry using generalized hydraulic geometry.

In the Case of Scenario C, the same approach indicated above would be used to estimate cross-sectional area as a function of stage. The corresponding discharge, however, would be estimated from the lidar surface velocity measurement. Standard hydraulic relationships based on turbulent velocity depth profiles indicate that cross-sectional average velocity is about 0.6 of the surface velocity. This relationship would form the basis for an initial estimate. Where ancillary information such as channel slope and roughness, are available, more sophisticated estimation methods could be used.

4.2. Lake and Wetland Storage Change

In addition to stage variations within river channels, information on water levels can be used to infer the storage and de-watering of lakes, artificial impoundments, and wetlands (Birkett 1998). See Figure 2. The appropriate calculation involves a stage height change and a corresponding plan area variation. Inland water body widths obtained from the Doppler-processing of the HYDRA-SAT radar altimeter source data must be interpreted in consideration of

the complete areal extent of the lake or inundated wetland as inferred by repeat passes over each candidate site. Areal extent of these water bodies can be verified through imagery from optical and/or SAR sensors. Examination of existing ERS-1/2 radar imagery is recommended for selected target areas that also have corresponding stage data in order to develop relations between along-orbit widths and true plan area. Pre-determined hypsometry (i.e. relation of stage to plan area) of target water bodies should also be obtained through ground-based survey and Lidar altimetry data sets. These tests will compare the performance of the hypsometric *versus* the imaging and the quasi-imaging approach with respect to volumetric changes.

5. RESEARCH NEEDS

The radar altimeter technology of HYDRA-SAT with respect to derivation of surface heights is well advanced in the case of both Scenario A and B. Indeed the demonstrated capacity of Geosat and T/P have proven the concept of retrieving open water elevations from space to be sound (Figure 2). In addition, for rivers, well-established and routine use of stage and river discharge makes it possible to develop an operational capacity that can monitor river discharges in large continental rivers from space. For lakes and wetlands, volumetric changes can be straightforwardly assembled by combining altimeter-derived stage and imaging data. With regard to the derivation of target widths, the implied technology for Mission Scenario B is sound but has not been previously applied to inland water targets.

The use of Doppler lidar (Scenario C) for observing river flow, on the other hand, is new and promising. As will be expressed later, there is a need to perform several paper and field studies before concluding the feasibility of the use of a Doppler lidar on HYDRO-SAT.

The next sections highlight several of the technical and science details that need to be further explored in order to meet the mission accuracy requirements as given in Section 3.3. and Tables 1 through 3. They are listed in order of priority and refer to paper, trade or field study type. Note that those with bold title and designated with an asterisk (*) refer to studies which already have been funded under the Land Surface Hydrology Program NRA-97-MTPE-12 (PI: L. Dingman) and 98-OES-11 (PI: C. Vörösmarty).

5.1. Technology (Trade) Studies

There are several broad classes of investigation needed to determine the optimal hardware/ software / platform / orbital configurations, parameters, and technical constraints associated with the Scenario A,B and C instrument packages. These engineering studies are recommended to assist in determining the quantity and quality of HYDRA-SAT inland water height and width data products that could

routinely be made available using the proposed technology.

- **Trade Study A: Vertical Height Accuracy**

Regarding achievable surface water height accuracy's, investigations will be needed to focus on:

- The improvement of derived altimetric range from the interpretation of specular waveforms. This should address all relevant hardware/software parameters including the selection of the chirp bandwidth.

- **Trade Study B: Surface velocity accuracy and resolution**

Regarding achievable surface velocity measurement accuracy, investigations will be needed to:

- How accurate can the surface velocity be measured with one lidar sample? This study would address the related issues of pointing control, point knowledge, signal processing and instrument laser pulse characteristics.

- **Trade Study C: Data Downloading and Processing**

A focused trade study will need to be instituted to address a suite of near-real time data set and data product delivery issues:

- Investigate whether near-real time FD data sets, at 20Hz height sampling with preliminary geophysical corrections, can be delivered by the ground processing teams within 1 day of satellite overpass;
- Assess whether orbit processing teams can deliver a 5cm rms preliminary orbit for its implementation into the FD datastream; and
- For Scenario C, assess the relative merits of on-board processing of the lidar data vs. downloading the raw signal.

- **Trade Study D: Global Coverage versus Optimal Re-visit Time(*)**

Design of HYDRA-SAT will require investigations into the spatial coverage versus temporal resolution problem, noting that the Science requirements dictate a 3-to-7 day temporal coverage. Studies need to be made of:

- Orbit scenarios including latitude range, noting number of target and validation site hits and trade-offs with repeat frequency.

- **Trade Study E: Repeat Track Drift**

It is essential that a reliable quantitative estimate be made of the accuracy along repeat tracks targeting the same inland water body. Along-track geo-location of the same target will require:

- Investigation into the requirement for repeat track drifts to be within $\pm 125\text{m}$ of a nominal ground reference track.

- **Trade Study F: Collaborative Scoping Studies with Ocean / Ice Communities**

Careful examination of trade-offs and opportunities to collaborate with the ocean and ice communities considering a shared future-instrument mission scenario. This has application to HYDRA-SAT mission Scenarios A,B and C. Particular attention will be drawn to:

- Future missions (Jason-1, Jason-2, ENVISAT, Polar Platforms) particularly regarding the possibility of dual-operating techniques via a simple ocean/land mask;
- Current incubator altimetric missions (microAlt/futureAlt/oceanAlt etc.), and
- Current lidar technology development within NASA laboratories

- **Trade Study G: Sensor Component Configurations**

A specific set of hardware, satellite, and orbital platform investigations need to be mounted into:

- The use of solid state technology, chirp and operating frequency constraints;
 - Antenna diameter constraints regarding signal/noise ratio;
 - Achievable operational lifetime; and,
 - Orbital scenarios to be considered regarding atmospheric drag, precise orbit determination and power usage.
 - Lidar/radar co-flight issues
- **Trade Study H: Data Downloading and Processing**

Based on optimal orbit configurations for inland stage, receiving station data ingest, and timely data processing requirements, procedures must be explored specifically to:

- Estimate Level 0 through 3 data volumes and throughput;
 - Investigate and develop the complete data processing sequences; and,
 - Identify ground gauges where the ability exists to telemeter real-time information to HYDRA-SAT and then subsequently download the data to a ground station. This will provide additional calibration and validation targets and also provide boundary conditions for interpolated stage and discharge estimates on rivers.
- **Trade Study I: Doppler Processing Using New Antenna Configuration**

This study refers to HYDRA-SAT Mission Scenario B and should address the following:

- Design of the 10m antenna i.e. determination of the optimal antenna reflector illumination in both the along and across-track directions; and,
- Testing the proposed instrument via airborne platforms prior to satellite deployment (**Field Study A**).

5.2. Paper Studies

There are additional technical studies which need to be undertaken to better clarify the specific attributes of HYDRA-SAT and to harmonize these with the

scientific requirements of the mission..

- **Paper Study A: Vertical Height Accuracy**

Regarding achievable surface water height accuracy by the HYDRA-SAT altimeter, investigations will be needed to clarify:

- The potential improvement of wet tropospheric and ionospheric model corrections that influence the overall accuracy of the derived surface height values.

- **Paper Study B: Doppler lidar velocity data product**

Scenario C of HYDRO-SAT introduces a number of issues that need to be explored before a final instrument suite can be defined for HYDRO-SAT:

- How can the radar altimeter and the Doppler lidar observations be co-ordinated? The lidar will also provide ranging data, but at slant angles of 30-45 degrees. Is this information useful for off-track (sub-satellite track) lidar observations?
- How will the surface velocity vs. stage data be accumulated for processing into discharge estimates for poorly gaged rivers?

- **Paper Study C: Doppler Processing of radar altimeter data**

Both Scenario A and B of the HYDRA-SAT mission can produce time series of varying along-track widths, from which river discharge and lake/wetland areas will be inferred. A specific set of investigations will be necessary to:

- Explore the interpretation of retrieved echoes for the determination of river widths. This is primarily a post-processing technique and a relatively new application for inland waters and the ERS mission will provide data for test case studies;

- Conduct an error analysis in terms of the possible contributions from vegetation, slope effects, and river surface roughness;
 - Validate preliminary results using airborne imaging sensors; and,
 - Investigate data processing algorithms.
- **Paper Study D: Global Coverage and Minimum Target Size (* in part)**

HYDRA-SAT will be required to offer maximum global coverage for all targets of sizes as specified in the Science Requirements section. Assessments will be made of:

- The selection of tracking logic. Ideally an agile tracker is required capable of acquiring the surface rapidly and robustly under extreme conditions of radar echo power and range. One that could gain lock for >75% of the surface within 0.5s would be advantageous for small targets;
 - The use and limitations of Digital Terrain Models and preset tracking i.e. general *a priori* knowledge of the expected surface elevations at a particular geographical location;
 - The selection of instrument footprint size and pulse duration;
 - The selection of telemetry/sampling rates;
 - The selection of pulse repetition frequency (PRF) and satellite orbital velocity for statistical independence of echoes;
 - The influence of complex topography and contaminating islands;
 - The influence of lake and ocean tides; and,
 - The effects of severe rain and wind storms, and river/lake ice formation and flows.
- **Paper Study E: Heritage Studies (*)**

Analysis of existing mission data sets will provide specific guidance in the design of HYDRA-SAT. Analysis should focus on:

- Performance of past and current instruments for inland water monitoring. This will include Geosat, T/P and the ERS

altimeter suites. Overall height accuracy, minimum target sizes, limitations and advantages will be sought.

- **Paper Study F: Regional-scale Inundation Status and Basin Topography**

An accurate determination of inundation extent will be necessary to adequately validate the along-track width product. This is necessary in order to develop relationships between these widths and (a) width perpendicular to river course, and (b) area of lakes/wetlands. This analysis would benefit from high resolution hypsometric maps of target sites linking stage to flooded area. Time series of inland water areal extent will therefore require investigation of:

- Non-commercial imaging radars (e.g. SARS, Quikscat) for obtaining wide-field inundation extents with L or C band and H-H polarization state. This will also provide a means of validating Doppler-derived river width depending on the resolution of the images. In addition, such imagery will serve as a guide for the interpretation of the radar altimeter echoes; and,
- Current and future satellite imaging instruments such as lidars (e.g. ICESAT) should be explored for information on basin topography (to assist in interpreting shoreline interference and to independently determine river/lake/wetland hypsography).

- **Paper Study G: Doppler Processing and Use of Land Reference Surface**

This refers to HYDRA-SAT Mission Scenario B and the application of *a priori* land surface specifications:

- Explore the self-calibration or 'land reference surface' technique for achieving desired height accuracy. This technique utilizes land surfaces that are available on each side of the target, along the same satellite overpass. It assumes good retrieval of altimeter height data over these regions, which act as reference surfaces. Normally suffering no temporal changes in height, any observed variations between repeat passes would thus be due to orbital and atmospheric effects. The derived magnitudes of these

variations can then be applied to the repeat pass height data over the inland water target in question.

5.3 Science Studies

The Science Strategy developed earlier in Section 4 presents a set of major research issues that need to be addressed before an operational, space-based satellite altimetry, velocity and quasi-imaging system can be applied to the inference of inland water state. Although the science behind the routine measurement of river stage, discharge, and inundation extent of lakes and wetlands is well-established, a coherent plan to utilize a satellite-based monitoring system requires specific feasibility studies. There also is a need for preliminary science studies to verify that the specific sensor, platform, and orbital configurations chosen will yield scientifically useful results.

- **Paper Study H: Discharge error analysis**

Although standard rating-curves used by hydrographic services to determine flow from stage height typically show errors of <10%, it is unclear what an associated error would be for an altimeter/velocimeter-derived signal from space. A science study is needed for:

- Estimation of the likely mission accuracy in terms of continental runoff, on a continent by continent basis. An assessment of which strategies for discharge estimation (given stage) would be applicable for an assumed orbital geometry, and what this would imply for discharge accuracy over a range of averaging intervals (daily, weekly, monthly).
- For Scenario C, determination of the accuracy in discharge estimation that would result using surface velocity measurements with specified errors in the likely range attainable by the lidar velocimeter, and subsequent derivation of rating curves based on a varying number of discharge estimates obtained using stage and width measurements obtained from radar altimeter Scenarios A and B. This study would best be performed for rivers within the targeted width range at locations currently monitored (e.g., by the U.S. Geological Survey) using in situ methods.

- **Paper Study I: Use of existing or discontinued gaging stations (*)**

HYDRA-SAT technical specifications such as a nominal footprint size of 250 m will limit the number of candidate river reaches and associated discharge monitoring stations for system calibration and validation. A geographic analysis of station distributions needs to be performed to:

- Determine the number of satellite-track – river intersections that are usefully close to existing or former gaging stations through overlays of modeled orbits and GIS mapping of channel networks;
 - Determine the precision with which discharge estimates can be made given the proposed vertical and horizontal resolution requirements (Section 3.3) by examining the slopes of rating curves for large rivers (USGS and other); and,
 - Estimate number of global locations where useful discharge measurements can be made using results from the previous steps.
- **Paper Study J: Use of satellite-derived cross-sections & general hydraulic relations (* in part)**

Well-established hydraulic geometry and flow relations should be explored from the standpoint of deriving satellite-based functions that could then be compared with results from land-based and modeling studies. Studies should be cast to:

- Validate use of channel/floodplain slope in general hydraulic relations. Obtain a number of measured cross-sections from USGS gages on large rivers; determine channel slope from maps, develop rating curves using Dingman and Sharma (1997) relation with channel slope, compare with measured USGS rating curves;
 - Determine the availability of maps, LIDAR, and SRTM information and suitability for converting satellite-track water-surface widths to perpendicular widths for use in hydraulic relations; and,
 - Create satellite-based analogs to these hydraulic relations.
- **Paper Study K: Use of bankfull hydraulic-geometry relations (*)**

Similar to stage-discharge, width-discharge relations and relations including slope, potentially derived from valley banks using LIDAR

or SRTM, need to be explored. A prescribed set of studies is outlined below:

- Select a number of USGS gaging stations on large rivers with well established rating curves. Use regional relations that give estimates of bankfull discharge and width based on drainage area and meander wavelength. Estimate channel slope from maps, satellite or airborne altimetry. Fit generalized cross-sections and construct synthetic rating curves using Dingman and Sharma (1997) relation. Compare with USGS rating curves.
- **Paper Study L: Use of imagery for lake/reservoir/wetland volume determination:**

Time-series of lake, reservoir, and wetland stage, combined with imagery can be used to infer time-varying water volumes. Studies are necessary that can provide:

- Estimation of the likely accuracy of derived standing water volumes from a synergistic combination of altimetric water level variations and imaging-derived surface areas; and,
- Development of methods to remotely monitor operating rules in artificial impoundments.

6. VALIDATION STRATEGY

6.1 Technical

The ground processing segments will routinely perform standard calibration and validation of the Level 0 data sets.

Validation of the Level 1,2,3 products produced by the inland water processing facility will be required. Validation of the derived time series of surface water levels (Level 1a and 2a) will be achieved via access to traditional gage data. Those satellite passes that fall within ± 5 km of a gage station will be chosen (with no significant tributary inputs), and comparison of the derived altimetric height time series, whether for a lake or river, will be interpolated to match the daily/hourly gage measurements from the stage. The root mean square (rms) value of the comparison will thus define the overall accuracy of the altimeter at that gage site. Many such validations may point to a general, globally-achievable accuracy useful for those regions where gage data are not obtainable. Validation of Level 1b products for river width or inundation extent may be difficult in an

absolute sense, but relative accuracy may be obtainable via comparison with measurements using other techniques. The latter will include aircraft aerial surveys and the use of satellite imagery. Validation of Level 1c and 2b (derived discharge values) can be performed via comparison with rating curves at selected gaging stations routinely collected by hydrographic services. Level 3 products (lake/reservoir volumes) will require imaging data and ground-based stage information to compute time-varying volume changes.

The sensor rms errors on stage or velocity need to be analyzed for their impact on discharge accuracy's and to place HYDRA-SAT performance into a comparative context versus standard land-based stage determinations. The precision with which discharge estimates can be made given the proposed vertical and horizontal resolution can be quantified by examining the slopes of rating curves for large rivers (obtained from USGS and other agency archives). Accuracy limitations are also imposed by HYDRA-SAT orbit repeat times. Tests can be performed on real station time series to explore the temporal sampling and revisit times of the satellite to optimize useful estimation of discharge (Figure 4).

7. SYNERGY WITH OTHER MISSIONS

The primary goal of HYDRA-SAT -- to obtain inland water height variations and river geometry -- will provide a critical information source for generating a picture of the status of rivers, lakes and wetlands. To be successful, however, it requires information from additional sensors. For example, although hampered by cloud conditions, various Lidar missions such as ICESAT could provide important topographical data within the river basin and thereby provide hypsometric information for interpreting inland water response to height variations. This topographical data will also be of use in interpreting bank effects as the sensor passes the interface between land and water. In addition, imaging radars such as RADARSAT, QUICKSCAT, the proposed freeze/thaw imager from this overall land surface hydrological monitoring mission, and standard NOAA/AVHRR imagery will offer large-scale viewing of target areas for assistance in the analysis of the enhanced radar altimetric data, particularly in complex terrain regions.

It can also be expected that several national and international inland water monitoring agencies would have an interest in the HYDRA-SAT Mission. Synergy with telemetered stations as part of WMO-W/HYCOS, UNESCO-FRIEND, USGS, Environment Canada, and other national and international monitoring agencies is anticipated. These agencies should be entrained into the planning of HYDRA-SAT at an early stage.

Another exciting area of potential synergism obtains from the fact that the Doppler lidar is, in reality, also a wind sensor. A Doppler lidar built to detect

returns from the Earth's surface will almost certainly be sensitive enough to sense the winds in the atmospheric boundary layer and the motion of most cloud material. These data would be of extreme value to those studying low level moisture transport and the relationship of cloud particle motion to cloud propagation.

8. MISSION-READINESS

Scenario A exploits the fact that several of the individual components of HYDRASAT utilize mature and mission-ready technologies and indeed, one technical study (Trade Study F) is recommended to examine tradeoffs and synergies with the ice and ocean communities in view of a joint mission. The altimeter itself could for example, be based on the T/P mission altimeter with modifications of onboard data storage to accommodate the Doppler processing technique. The microwave radiometer and telemetry relay system also have spaceborne counterparts that have operated successfully for years. Together these systems constitute a relatively simple hardware/software suite based on existing technology at substantial savings in overall hardware costs for the mission. Although the Scenario B radar system requires development and validation, the theory upon which it is based has been proven, and proposed scoping activities (including airborne testing) should ensure its successful application on a space-based platform. As for Scenario C, the Doppler lidar (Scenario C) is based upon proven technology but will require a paper study and a field demonstration before committing to a space-flight.

REFERENCES

- Au, A.Y., R.D. Brown, and J.E. Welker. 1989. Analysis of altimetry over inland seas. NASA Tech. Memo., 100729.
- Birkett, C.M. 1994. Radar altimetry: A new concept in monitoring lake level changes. EOS Trans. 75(24), 273-275.
- Birkett, C.M. 1995. The contribution of TOPEX/POSEIDON to the global monitoring of climatically sensitive lakes. JGR-Oceans 100(C12), 25179-25204.
- Birkett, C.M. and G. Kite. 1997. Derivation of lake areas and elevations for the Mackenzie Basin using satellite remote sensing. In "Application of Remote Sensing in Hydrology", proc. NHRI Symposium No. 17, ISBN 0-660-16691-X, ISSN 0838-1984.
- Birkett, C.M. 1998. Contribution of the TOPEX NASA radar altimeter to the global monitoring of large rivers and wetlands. Water Resour. Res. 34(5), 1223-1239.

Birkett, C., R. Murtugudde, and T. Allan. 1999. Indian Ocean climate event brings floods to East Africa's lakes and the Sudd Marsh. *Geoph. Res. Letters* 26(8), 1031-1034.

Bray, D.I., 1979. Estimating average velocity in gravel-bed rivers. *ASCE Journal of the Hydraulics Division* 105(HY9), 1103-1122.

Brooks, R.L. 1982. Lake elevations from satellite radar altimetry from a validation area in Canada. Report, Geosci. Res. Corp., Salisbury, Maryland, U.S.A.

Cazenave, A., P. Bonnefond, K. Dominh, and P. Schaeffer. 1997. Caspian sea level from Topex-Poseidon altimetry: Level now falling. *Geophy. Res. Letters* 24(8), 881-884.

Coe, M.T. 1998. A linked global model of terrestrial hydrologic processes: Simulation of rivers, lakes, and wetlands, *J. of Geophys. Res.* 103 (D8), 8885-99.

Cudlip, W., J.K. Ridley, and C.G. Rapley. 1990. The use of satellite radar altimetry for monitoring wetlands. In "Remote Sensing and Global Change", Proceedings of the 16th Annual Conference of the Remote Sensing Society, Swansea, 207-216.

Dalton, J.A., and G.W. Kite. 1995. A first look at using the TOPEX/POSEIDON satellite radar altimeter for measuring lake levels. In: *Remote Sensing in Hydrology*, Proc. Symp. No.14, NHRI, Saskatoon, Canada, ed. G.W. Kite, A. Pietroniro and T.D. Pultz, 105-112.

Dingman, S.L., and K.J. Palaia. In Press. Comparison of models for estimating flood quantiles in New Hampshire and Vermont. *Journal of the American Water Resources Association*.

Dingman, S.L., and K.P. Sharma. 1997. Statistical development and validation of discharge equations for natural channels. *Journal of Hydrology*, 199, 13-35.

Dury, G.H. 1976. Discharge prediction, present and former, from channel dimensions. *Journal of Hydrology*, 30, 219-245.

Fekete, B.M., C.J. Vörösmarty, and W. Grabs, 1999. An Improved Spatially-Distributed Global Runoff Data Set Based on Observed River Discharge and Simulated Water Balance. WMO-Global Runoff Data Center Report. In press.

Grabs, W. et al. 1996. Freshwater fluxes from continents into the World Oceans based on Data of the Global Runoff Data Center, GRDC Report No.10, Koblenz, Germany.

Graham, S.T., F.S. Famiglietti, and D.R. Maidment, Five-minute, 1/2°, and 1° data sets of continental watersheds and river networks for use in regional and global hydrologic and climate system modeling studies. *Water Resources Research*, 35, 583-87.

Guzkowska, M.A.J., C.G. Rapley, J.K. Ridley, W. Cudlip, C.M. Birkett, and R.F. Scott. 1990. Developments in inland water and land altimetry, ESA Contract, CR-7839/88/F/FL.

Henderson, F.M. 1966. *Open Channel Flow*. Macmillan, New York, 522pp.

Hirsch, R.M., 1999. The USGS streamgaging network, *GeoTimes* April 1999, 20-24.

Koblinsky, C.J., R.T. Clarke, A.C. Brenner, and H. Frey. 1993. Measurement of river level variations with satellite altimetry, *Water Resour. Res.* 29(6), 1839–1848.

Korzoun, V. I., A. A. Sokolov, M. I. Budyko, K. P. Voskresensky, G. P. Kalinin, A. A. Konoplyantsev, E. S. Korotkevich, and M. I. Lvovich, 1978. *Atlas of World Water Balance*. UNESCO, Paris.

Ludwig, W. and J.-L. Probst, 1998, River sediment discharge to the oceans: Present-day controls and global budgets, *American J. of Science* 298, 265-295.

Morris, C.S., and S.K. Gill. 1994a. Variation of Great Lakes water levels described from Geosat altimetry, *Water Resources Research* 30(4), 1009-1017

Morris, C.S., and S.K. Gill. 1994b. Evaluation of the TOPEX/POSEIDON altimeter system over the Great Lakes, *J. Geophys. Res.* 99(C12), 24527–24539.

Oki, T., K. Musiake, H. Matsuyama and K. Masuda, 1995. Global atmospheric water balance and runoff from large river basins. *Hydrological Processes*, 9, 655-678.

Olliver, J.G. 1987. An analysis of results from SEASAT altimetry over land and lakes. Paper presented at IAG Symposium, IUGG XIX General Assembly, Int. Assoc. of Geod., Vancouver.

- Osterkamp, W.R., L.J. Lane, and G.R. Foster. 1983. An analytical treatment of channel-morphology relations. U.S. Geological Survey Professional Paper 1288.
- Ponchaud, F. and A. Cazenave. 1998. Continental Lake Variations from Topex/Poseidon (1993-1996). C.R. Academie des Sciences, Earth Planetary Sciences, 326, 13-20.
- Rapley, C. G., M.A.J. Guzkowska, W. Cudlip, and I.M. Mason. 1987. An exploratory study of inland water and land altimetry using Seasat data. ESA Rep. 6483/85/NL/BI, Eur. Space Agency, Neuilly, France.
- Rosgen, D. 1996. Applied River Morphology. Wildland Hydrology, Pagosa Springs, CO.
- Sahagian, D. L., F. W. Schwartz, and D. K. Jacobs. 1994. Direct anthropogenic contributions to sea level rise in the twentieth century. Nature 367: 54-56.
- Seitzinger, S.P., and C. Kroeze. 1998. Global distribution of nitrous oxide production and N inputs in freshwater and coastal marine ecosystems. Global Biogeochemical Cycles 12, 93-113.
- Shiklomanov, I.A. and A.A. Sokolov. 1983. Methodological basis of world water balance investigation and computation. In: New Approaches in Water Balance Computations. International Association of Hydrological Sciences Publ. #148. Wallingford, UK.
- Smith, L.C., B.L. Isacks, A.L. Bloom, and A.B. Murray. 1996. Estimation of discharge from three braided rivers using synthetic aperture radar satellite imagery. Water Resources Research 32(7):2021-2034.
- Smith, L.C. 1997. Satellite remote sensing of river inundation area, stage, and discharge: A review. Hydrological Processes, 11, 1427-1439.
- Tian, H. et al. 1998. Effect of climate variability and increasing atmospheric CO₂ on carbon storage in undisturbed Amazonian ecosystems. Nature. In review.
- USGS-EDC, Global 30-arc second elevation data set (GTOPO30), US Geological Survey, Earth Resources Data Center, Sioux Falls SD, Data base found at: <http://edcwww.cr.usgs.gov/>.
- Vörösmarty, C.J. and D. Sahagian. 1999. Anthropogenic disturbance of the terrestrial water cycle: Global-scale impacts from hydraulic engineering works. BioScience (In review).

Vörösmarty, C.J., B. M. Fekete, and M. Meybeck. 1999. A simulated topological network representing the global system of rivers at 30-minute spatial resolution (STN-30). *Global Biogeochemical Cycles*. In press.

Vörösmarty, C. J., K. P. Sharma, B. M. Fekete, A. H. Coprland, J. Holden, and others. 1997a. The storage and aging of continental runoff in large Reservoir systems of the world. *Ambio* 26: 210-219.

Vörösmarty, C.J., M. Meybeck, B. Fekete, and K. Sharma. 1997b. The potential impact of neo-Castorization on sediment transport by the global network of rivers. In: D. Walling and J.-L. Probst (eds.), *Human Impact on Erosion and Sedimentation*, pp. 261-72. IAHS Press, Wallingford UK.

Vörösmarty, C.J., R. Wasson, and J.E. Richey (eds.). 1997c. *Modeling the Transport and Transformation of Terrestrial Materials to Freshwater and Coastal Ecosystems. Workshop Report and Recommendations for IGBP Inter-Core Project Collaboration. IGBP Report #39. IGBP Secretariat, Stockholm*

Vörösmarty, C.J., B. Fekete, and B.A. Tucker. 1996a. *River Discharge Database, Version 1.0 (RivDIS v1.0), Volumes 0 through 6. A contribution to IHP-V Theme 1. Technical Documents in Hydrology Series. UNESCO, Paris.*

Vörösmarty, C.J., C.J. Willmott, B.J. Choudhury, A.L. Schloss, T.K. Stearns, S.M. Robeson, and T.J. Dorman. 1996b. Analyzing the discharge regime of a large tropical river through remote sensing, ground-based climatic data, and modeling. *Water Resources Research* 32: 3137-50.

Wahl, K.L., W.O. Thomas, and R.M. Hirsch. 1995. *Stream-gaging program of the U.S. Geological Survey. USGS Circular 1123. USGS, Reston VA.*

Williams, G.P. 1978. Bankfull discharge of rivers. *Water Resources Research*, 14(6), 1141-1154.

APPENDIX A

HYDRA-SAT Scenario B Concepts

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Summary: To develop a radar system design capable of performing two tasks:

- Determine water level with centimetric accuracy for medium sized rivers and lakes.
- Determine water boundaries in the along-track direction with a planimetric accuracy of a few meters.

The system consists of a high-bandwidth single frequency radar altimeter with synthetic aperture processing used to obtain the along-track spatial resolution and a large antenna to obtain the cross-track resolution (see Radar Block diagram).

Performance Goals: It is desired that a radar system be developed to meet the following goals:

- Along-Track Spatial Resolution: 5m (5 Looks)
- Height Accuracy Relative to Surrounding Land: 1 cm
- Cross-Track Resolution: <900m (beam limited) 1km (pulse limited)
- Coverage: Selected coverage over desired rivers and lakes (not global coverage)

System Parameter Trade-Off Considerations:

Orbit Selection: Traditionally, ocean altimeters have selected high orbits to minimize tidal aliasing of ocean signals and to make orbital estimation easier. Due to GPS technology, and to the fact that orbital errors are long wavelength and will be removed by the land tie-pointing procedure discussed below, lower orbits become feasible. This significantly aids the instrument cross-track resolution, decreases problems due to the ionosphere, reduces instrument power and radiation requirements, and decreases launch costs. Given these considerations, we select a 400km altitude orbit. The main requirement on the orbit is that it repeat within 250m, in order to enable the land tie-pointing procedure described below. This requirement is achievable with current technology.

Frequency: In order to minimize antenna dimensions and the effect of ionospheric delays, as well as to allow for high transmitted signal bandwidths, it is desirable to go to as high a frequency as possible. Practically, this implies that either Ku-band (13.6GHz) or Ka-band (35 GHz) be used, given current technology. The relative advantages and disadvantages of these frequencies are listed below:

Ku-band advantages:

- More mature technology: 5-Watt spaceborne solid state power amplifiers currently exist.
- Smaller temporal decorrelation of land signals when using coherent repeat pass processing.
- Lower atmospheric and water vapor attenuation: all weather.

Ku-band disadvantages:

- Lower allocated frequency bandwidths (about 400MHz) imply degraded height resolution.
- Ionospheric errors are six times larger than at Ka-band.
- Larger required antenna for the same cross-track resolution.

Ka-band advantages:

- Smaller ionospheric errors.
- Smaller antenna required.
- Higher bandwidth (i.e., height resolution) possible.

Ka-band disadvantages:

- Technology less mature: 1-Watt solid state power amplifier feasible, but not yet built.
- Higher tropospheric attenuation: may not work in heavy rain.
- Larger temporal decorrelation for coherent repeat pass processing.

Given these considerations, both frequencies should be studied and the final frequency selection should be made after a more detailed study.

Ionospheric Errors: The ionospheric errors have very long (>100km) wavelengths, so that the effect of the ionosphere on the return heights will be to introduce a height bias and tilt in the estimated profile. Currently, global ionospheric maps are being generated from GPS measurements. These maps are sufficient to provide a full correction of the ionospheric delay at Ka-band, but are not sufficient at Ku-band. If Ku-band is selected, ionospheric errors would be removed with the land tie-pointing procedure outlined below. Traditional altimeters (i.e., TOPEX) use a second frequency (C-band: 5GHz) to remove ionospheric errors. However, the antenna dimensions required to achieve the desired cross-track resolution are prohibitive at C-band with the current design.

Tropospheric Delays: Tropospheric errors can be separated into two components: dry and wet. The dry troposphere contribution has a long wavelength signature, and can be removed using pressure models. The wet tropospheric contribution exhibits a power law behavior, with the long wavelength components accounting for the bulk of the delay. However, even the shorter wavelength components are large compared to the accuracy required by the proposed instrument. While total delays due to the troposphere can be as large as 30 cm, the delays are geographically correlated and the quantity of interest is then the difference in delays over the same point over different days. Appendix Figure 1 presents one-way range delays for a globally distributed data set obtained from radiosonde data. These data show that the rms one-way delay is always under 5 cm, making our problem somewhat simpler.

Traditional altimeters use three-frequency radiometry to correct for wet tropospheric delays, and can achieve centimetric accuracy in the correction. However, this technique is not suitable for our application for a variety of reasons: 1) the radiometer observed temperatures are dominated by surface temperature, not by tropospheric contributions; 2) there are no models for inverting the delay from land surface returns; 3) the radiometer resolution is many orders of magnitude (40km for TOPEX) worse than the one required for this application.

Self Calibration for Media/Orbit Errors:

Instead of trying to achieve absolute ranging, the present concept uses the fact that both ionospheric, and orbit corrections have scales which are large compared to the desired resolution. The tropospheric delays can have short scale variations, but by averaging over a large enough window, these fluctuations can be reduced. By estimating the land topography on the boundaries of the river or lake, it is possible to use these measurements over the (presumably) stable land surface to correct for the propagation on orbit errors, yielding a highly accurate **relative** measurement of the river level and the surrounding topography. The use of a repeat pass orbit would guarantee that the same land topography is used for the calibration of each crossing. An advantage of this

calibration scheme is that it obviates the need for additional instruments to make the range corrections, and significantly reduces the requirements on the orbit determination.

The amount of data required to achieve appropriate accuracy for the land topography depends on the method used to monitor the changes in range between repeat passes. The most sensitive method, which has been extensively demonstrated in repeat pass interferometry, involves the estimation of the differential phase between the received signals. For this method to work, it is required that the surface not change significantly (compared to the radar wavelength) between passes. Experimental observations using C-band show that, as long as the vegetation is not tropical, significant correlation can persist over long periods of time. There is currently no data on the repeat pass correlation for Ku or Ka-band data, but it is expected that the correlation will drop as the frequency increases. Whenever the correlation is high enough (0.3-0.4), this method has the potential of yielding very accurate (fraction of a wavelength) estimates of any changes in the range, without averaging over very large scales.

Since the correlation properties of the radar returns at high frequencies are not well known, a more conservative approach is to estimate the data required using amplitude (not phase) altimetry. We are interested on how well range measurements over land will repeat using data from different passes, not on how well the land topography itself is measured (this can be significantly worse). Assuming orbit repeatability of better than 250m and taking into account the tropospheric delay variations shown in Appendix Figure 1, we estimate conservatively that, after taking 100 looks (averaging over 100 m along-track) the range to land can be repeated with a range noise of 30 cm. Given this assumption, averaging for 45 km on either side of the crossing is required in order to obtain a tie-point accuracy of 1 cm.

Resolution: The along-track system resolution is obtained using conventional full synthetic aperture processing. As is well known, the achievable resolution is 1/2 the antenna length. In our design, this translates to an along track resolution of 1m. In the cross-track direction, the resolution over land (where, unlike the ocean, significant topographic variations can occur in small spatial scales) is determined by the altimeter cross-track beamwidth. In order to achieve resolutions which are better than 1km, a large antenna width is required: 10m for Ku-band and 5m for Ka band. These antennas are the key technological challenge for the present mission design: they are currently feasible from a technological point of view, but have not yet been demonstrated in a spaceborne mission.

System Concept: We propose a downward looking coherent beam-limited altimeter system at Ku-Band, with synthetic aperture processing to be performed on the ground. The along track resolution is achieved using synthetic aperture. The cross-track resolution is achieved by a long antenna in the cross-track

direction. The height accuracy is obtained by waveform fitting the altimeter range and azimuth compressed signal. Resolution to better than the radar bandwidth (super-resolution) is achieved by interpolating the coherent return signal in range and fitting against a beam-limited altimeter waveform model. We use the fact that nadir returns from rivers and clam lakes have a significant coherent component to reduce the number of looks required to process the data to the desired accuracy. The key system parameters for such a system using Ku and Ka-Band frequencies are listed in Appendix A and B, respectively.

Key Differences with Traditional Altimeters:

1- No dynamic range tracking: Nadir looking altimeters are often not able to acquire data over land due to the fact that land waveforms are quite different from ocean waveforms, and the onboard dynamic tracker cannot lock onto the land signal. This problem can be overcome using digital elevation models (DEM's) such as the NIMA DTED-I or the SRTM global data set to preset the range window over the locations of interest. This significantly simplifies onboard processing requirements. The preset range can be fine-tuned during the mission.

2- Coherent SAR Processing: The along track resolution is obtained by using full coherent SAR processing. The data is collected on board and downlinked and fully processed on the ground. Full deramp compression is used onboard to reduce the data bandwidth and perform range compression (as in standard altimeters), but the waveforms are not incoherently averaged. The achievable resolution is half the antenna dimension in the along-track direction.

Targeted Data Collection:

To reduce data volume, the instrument will only acquire data over designated rivers and lakes, making the data storage and downlink requirements manageable, even for full SAR processing.

Table A: Ku-Band Design Details

System Parameters:

Transmit Power (W)

5.00

Frequency (GHz)	13.60
Wavelength (cm)	2.21
Pulse Length (muSec)	50.00
Bandwidth (MHz)	400.00
Antenna Width (m)	10.00
Antenna Length (m)	2.00
Platform Height (km)	400.00
PRF (KHz)	7.00
Range Window (m)	100.00
Along-Track Resolution (1-Look) (m)	1.00
Cross track resolution (m)	882.35
Pulse limited resolution (m)	1062.67
Fresnel Zone Diameter (m) 2	66.4

Link Equation

Power (dB)	6.99
Area (dB)	59.72
sigma0 (dB)	5.00
Two way gain (dB)	108.26
Two way propagation losses	-246.07
Compression gain (dB)	43.01
$\lambda^2/4\pi$	-44.12
System losses	-8.00
Atmospheric losses	-3.00

Received Power (dBW)	-78.21
Boltzmann constant (dB)	-228.60
System Temperature (dB)	30.00
Bandwidth (dB)	86.02

Noise Power (dbW)	-112.58
SNR (dB)	34.37

Data Volume Calculation

Height noise/100 Looks (cm)	30.00
Averaging distance (km)	90.00
# bits/sample	8.00
# of samples/range line	266.67
Megabytes/crossing	192.00

Table B: Ka-Band Design Details

Key System Parameters:

Transmit Power (W)	1.00
Frequency (GHz)	35.00
Wavelength (cm)	0.86
Pulse Length (muSec)	50.00
Bandwidth (MHz)	800.00
Antenna Width (m)	5.00
Antenna Length (m)	2.00
Platform Height (km)	400.00
PRF (KHz)	7.00
Range Window (m)	100.00
Along-Track Resolution (1-Look) (m)	1.00
Cross track resolution (m)	685.71
Pulse limited resolution (m)	751.42
Fresnel Zone Diameter (m) 2	41.40

Link Equation:

Power (dB)	0.00
Area (dB)	57.12
sigma0 (dB)	0.00

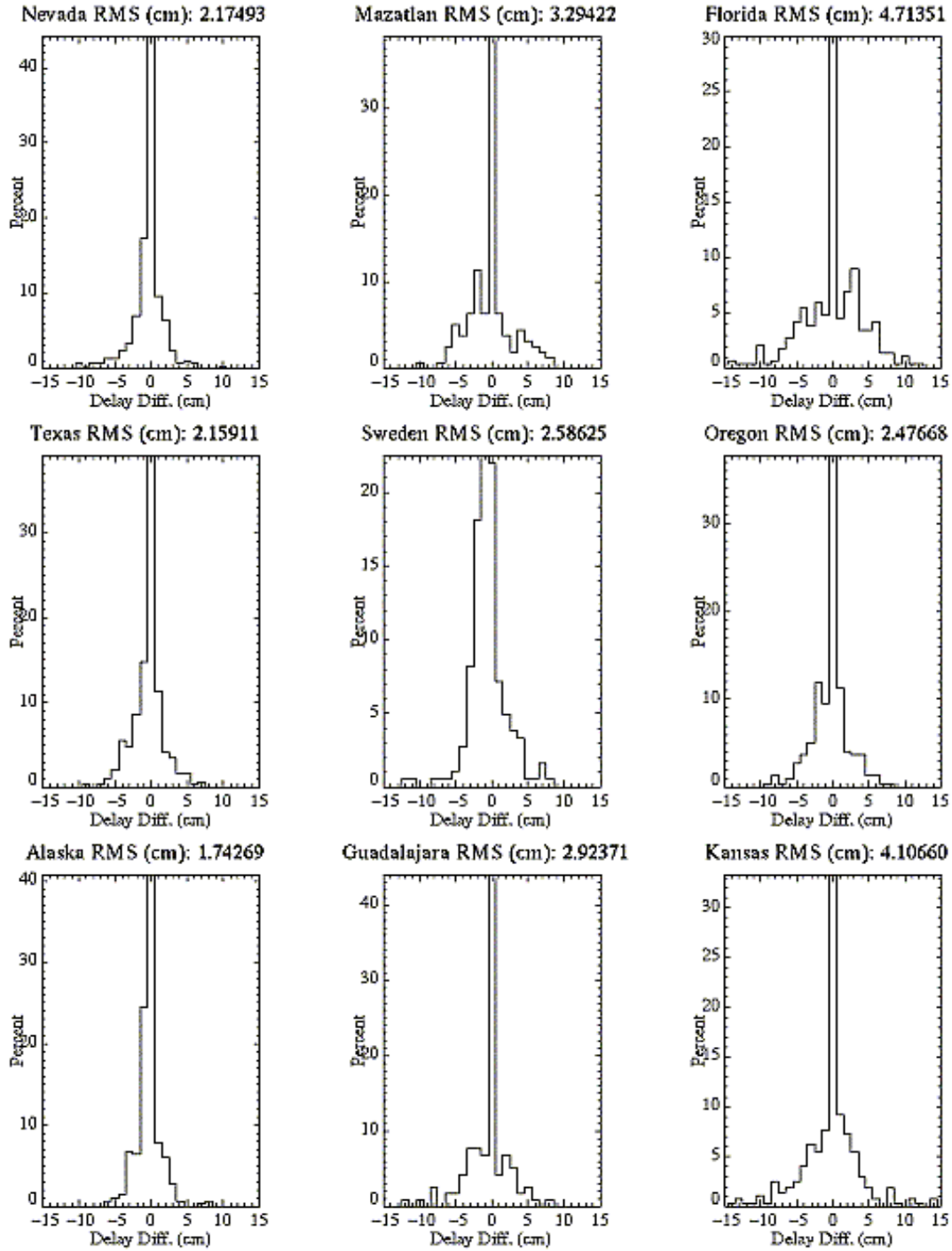
Two way gain (dB)	118.66
Two way propagation losses	-246.07
Compression gain (dB)	46.02
$\lambda^{2/4\pi}$	-52.33
System losses	-10.00
Atmospheric losses	-9.00

Received Power (dBW)	-95.59
Boltzmann constant (dB)	-228.60
System Temperature (dB)	30.00
Bandwidth (dB)	89.03

Noise Power (dbW)	-109.57
SNR (dB)	13.97

Data Volume:

Height noise/100 Looks (cm)	30.00
Averaging distance (km)	90.00
# bits/sample	8.00
# of samples/range line	533.33
Megabytes/crossing	384.00



Appendix Figure 1: Wet tropospheric one-way range delay differences between radiosonde measurements at different times of day for widely distributed geographical locations. Although total delays can be as large as 30 cm, due to the geographical correlation of the errors delay standard deviations for any single site are substantially smaller.

FIGURE CAPTIONS

Figure 1. Time series of discharge gaging stations held by the WMO Global Runoff Center (top curve), a central repository for observations of continental runoff (Fekete et al. 1999) and that held within the University of New Hampshire RivDIS database (bottom curve, Vörösmarty et al., 1996a). Abandonment of stations, closure of previously open data sets, and delays in data processing conspire to limit the real-time value of these data sets.

Figure 2. Time series of TOPEX/POSEIDON level changes for Lake Chad, the Southern Aral Sea, the Amazon River, and Tonle Sap. Note the comparison between the Amazon altimetry results and gauge data at Manacapuru (solid line). The altimeter is both able to monitor rivers and their floodplains (e.g. Tonle Sap). Note the rising levels of lake Chad, while the Aral Sea has decreased by 2.5m between 1993 and 1997.

Figure 3. Orbital analysis applied to reaches of the Columbia River in eastern Oregon. Optimal orbit configuration and data transmission rates from HYDRA-SAT need to be established. A GIS-based analysis of the type shown above is required.

Figure 4. Impact of alternative temporal sampling strategies of daily discharge. An optimal repeat cycle of HYDRA-SAT will need to be determined. It is anticipated that a 7-10 day re-visit time would be sufficient for large rivers. (From: Smith et al. 1997).