The Ka-band SWOT Phenomenology Airborne Radar (KaSPAR): A Novel Multi-baseline Interferometer for SWOT Characterization, Calibration and Validation

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Executive Summary

In this white paper we present an airborne sensor that will support pre-mission science and mission calibration and validation for the Surface Water and Ocean Topography (SWOT) mission. SWOT is unique and distinct from precursor ocean altimetry missions in some notable regards: 1) 100km+ of swath will provide complete ocean elevation coverage; 2) in addition to the ocean product, land surface water will be mapped for storage measurement and discharge estimation; and 3) Ka-band single-pass interferometry will produce the height measurements introducing a new transmit frequency and measurement technique. The introduction of this new approach provides additional algorithmic, characterization and calibration/validation needs. To uniquely fulfill these needs, we present here the Ka-band SWOT Phenomenology Airborne Radar (KaSPAR) to complement traditional ocean altimeter calibration/validation campaigns and measurements and existing and planned surface water gauge networks.

KaSPAR is a modular system with multiple temporal and cross-track baselines to fully characterize the scattering and statistics expected from SWOT, supply data for developing classification algorithms, and provide an understanding of instrument performance and limitations over the vast variety of scenes that SWOT will encounter (ie sea-ice, vegetation covered water, frozen/partially frozen rivers etc). Furthermore a wide-swath (>5km) high-accuracy elevation mapping capability provides the necessary framework to translate traditional point or profile calibration/validation measurements to the spatial framework that SWOT will measure.

KaSPAR has several key design principals:

1. The receiver channel architecture is modular and receivers are essentially identical in terms of hardware to ensure channel-to-channel calibration and minimize risk and cost,
2. As much as possible, existing designs for key components (antennas, mechanical design and receiver hardware) will be leveraged to minimize cost, risk and schedule, and
3. The system is compact with the antenna "panel" being a drop-in design that is compatible with multiple aircraft platforms. For example, the KaSPAR design and performance is compatible with NASA Langley and NASA Dryden King Airs *with little to no aircraft modifications*. However, all hardware is specified for compatibility with high-altitude operation on a Global Hawk (e.g. hardware is conduction cooled, and altitude specifications are given to 70,000ft).

In summary, this white paper presents an airborne sensor that will support SWOT throughout all phases including science and algorithm development and calibration and validation. The ability of KaSPAR to collect data "on-demand" holds great potential to augment the science impact of

SWOT since KaSPAR could be strategically deployed during time-critical events such as floods. Furthermore, KaSPAR can extend the scientific return on investment by extending SWOT observations in scientifically significant regions. For example, KaSPAR will be capable of providing interim data between overpasses for highly dynamic smaller rivers to validate data assimilation schemes, or KaSPAR data can quantify discharge contributions of tributaries too small to be imaged by SWOT. Beyond SWOT, KaSPAR's unique 4D imaging capability (2D intensity, elevation and velocity mapping) can be uniquely applied to topography applications, local water resource management and monitoring, weather reconnaissance (e.g. floods & storm surge), airborne electronic vision applications and much more.

1 Motivation

A long history of spaceborne radar altimetry observations of the ocean surface has revolutionized oceanography enabling significant advances in our understanding of global ocean circulation [e.g., Fu and Cazenave, 2001]. More recently these measurements (in the last decade) have been extended to provide elevation measurements of land surface water bodies (ie lakes, rivers and floodplains) [e.g. Birkett 1995, 1998; Birkett et. al. 2002; Alsdorf et. al. 2007a]. Despite the significant contributions of these observations, the fundamental limitation presented is the lack of coverage that a conventional nadir-looking sensor can provide with gaps between satellite tracks of 200-300km. The result is that smaller scale features (e.g., oceanic mesoscale processes) are not resolved and many rivers and lakes are not observed altogether [Alsdorf et.al. 2007b]. Both the oceanography and the surface water hydrology science communities recognized this fundamental shortfall and responded to the National Research Council (NRC) Earth Science Decadal Survey with independent concepts for swath-mapping interferometric radar missions.

In response the NRC Decadal Survey [*Anthes and Moore*, 2007] acknowledged not only the compelling science needs, but also the measurement commonality between the ocean and surface water communities by recommending the two communities unite for the Surface Water Ocean Topography satellite mission (SWOT). To satisfy the high-resolution sampling requirements needed for surface water hydrology, and the high accuracy requirements for oceanography, the primary SWOT instrument is a Ka-band Radar Interferometer (KaRIN). This solution is capable of simultaneously meeting coverage, accuracy and resolution requirements of both communities and greatly enhances the science achievable from a traditional profiling altimeter. In particular, by looking at a range of near-nadir incidence angles (from $\theta_i \sim 1^o$ to 6^o), the coverage of KaRIN is substantially greater than that of conventional altimetry. A Ka-Band center frequency provides a high level of accuracy, at a technologically feasible baseline, whilst still penetrating clouds and light rain. However the uniqueness of this solution, and application, means there remain some specific questions for which there currently exists little or no supporting data.

In this white paper we present the Ka-band SWOT Phenomenology Airborne Radar (KaSPAR) as a sensor that can provide supporting measurement and science data to extend and accelerate SWOT science and mission activities. Figure 1 shows a cartoon concept of KaSPAR which has a narrow "SWOT-like" sub-swath coupled with a wider high accuracy elevation-mapping swath. KaSPAR's goals are two-fold:

1. To mimic and characterize the SWOT geometry, scattering and sampling (i.e. be "SWOT-like") for a variety of targets and,
2. To provide a high accuracy, high-resolution elevation swath-mapping capability for pre-mission science interpretation and algorithm and for subsequently for mission calibration and validation.

These objectives are summarized in more detail in Sections 1.1 and 1.2.

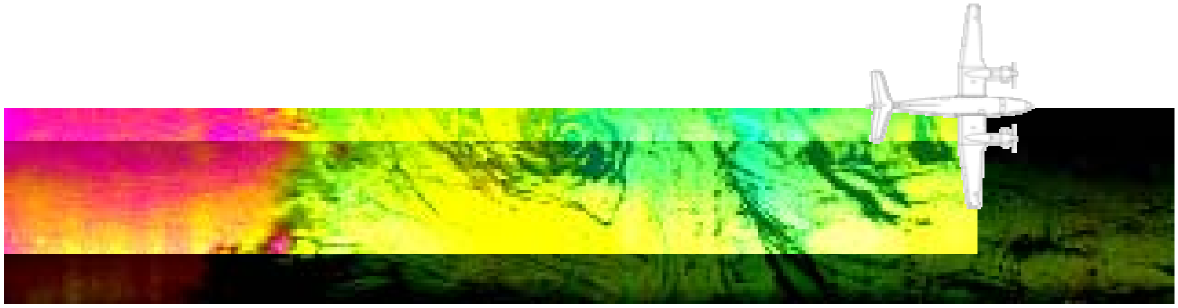

Figure 1: Cartoon concept of KaSPAR with two overlapping swaths

1.1 SWOT Phenomenology and Characterization

KaSPAR will mimic and characterize SWOT by replicating the incidence angles and interferometric relationships of the SWOT design but from airborne altitudes. The flexibility of an airborne sensor will allow targeted regions of observation to span the science range of interest – therefore mimicking SWOT performance not only over the primary SWOT science targets - namely ocean, large rivers and large lakes – but also to maximize potential science return by collecting data where SWOT performance predictions are less understood, for example:

1. Vegetated regions (wetlands, marshes, mangroves),
2. Sea-ice,
3. Ice-covered lakes or rivers including observations of ice-breakup,
4. Flood-plain terrain mapping,
5. Coastal regions and estuaries.

This will predominantly be achieved by the near-nadir narrow swath that replicates the SWOT range of incidence angles. KaSPAR will provide the following measurements:

1. Normalized radar cross-section as a function of incidence angle ($\sigma_0(\theta_i)$),
2. Temporal coherence of the water (τ_c)
3. Water elevation map over the SWOT range of incidence angles. For this the interferometric baseline is specifically chosen to be directly analogous to KaRIN as you scale the geometry, but with a bandwidth greater than KaRIN to provide additional resolution.

1.1.1 Relationship to Previous Research/Observations

Ocean scattering observations using Ka-band at near-nadir has been published by Walsh et.al., [2008], Vandemark et.al [2004] and Tanelli et.al. [2006]. From measurements obtained with the NASA Scanning Radar Altimeter, [Walsh et.al, 2008] characterize the dependence of the ocean surface σ_0 on incidence angle from nadir to approximately 25 degrees for low to gale force ocean surface wind speed conditions. However, radar observations of freshwater bodies are very limited both at Ka-band frequencies and for near-nadir incidence angles [Vandemark et.al, 2004, Moller and Rodriguez, 2007]. Vandemark et.al. presented limited nadir σ_0-derived surface slope observations of a single inland water body as a point of comparison for their more substantial ocean observations. Moller and Rodriguez deployed a bridge-based Ka-band radar at several diverse river and reservoir locations in Ohio (later extended to include sites along the Sacramento river). These observations were limited in scope but delivered formative data that demonstrated a great degree of sensitivity of the radar backscatter to the local meteorological and surface conditions. Specifically:

1) The angular characteristic of the backscatter ($\sigma_0(\theta_i)$) decay can vary greatly from a very strong specular return and sharp decay, to a more moderate nadir-return with a slow decay as θ_i increases to 5-6^o.
2) The surface temporal decorrelation ranged from just a few ms to tens of ms.

An implication from the $\sigma_0(\theta_i)$ measurements is that, for very low wind-speed conditions and little turbulence-induced roughness there may be narrowing of the achievable swath for SWOT over land due to σ_0 decay. Furthermore, and importantly, rapid temporal decorrelation will limit the azimuth resolution of SWOT which in turn may limit the ability of KaRIN to accurately specify the spatial extent of the water body: a key variable in storage and discharge calculations. For this reason understanding the dynamics of the temporal decorrelation for different surface (current induced turbulence) and meteorological (primarily wind) conditions is key for predicting storage change and discharge accuracies in a manner which is scalable to the global coverage of SWOT. Additionally, with data from KaSPAR, we could evaluate the possibility of synthesizing different length apertures to infer decorrelation through comparative “smearing” of the land/water boundaries. This may lead to a processing methodology for correction of the along-track “widening” of water mask which will vary with the surface correlation. With the measured decorrelation times as “truth” (not directly available from KaRIN) we will be able to fully verify our algorithms and quantify the performance gains.

The bridge-based observations by Moller and Rodriguez, while informative are limited by radar footprint and the portability of the ground-based configuration. In May 2009, a limited amount of Ka-band airborne data was collected by the GLISTIN airborne system in support of SWOT [Moller, 2009]. While the first of its kind and a valuable contribution, this system is not optimized for the near-term, or long-term needs of SWOT. Most notably the interferometer is off-nadir looking (31^o) and limited to 80MHz bandwidth (KaRIN is 200MHz and KaSPAR is 450MHz to over characterize SWOT). To compensate for the incidence angle incompatibility the aircraft was rolled toward nadir during GLISTIN data collections but this is clearly not an optimal solution.

KaSPAR can extend the ground and airborne work by gathering more statistics from a wide variety of open water bodies (lakes, reservoirs and varying size rivers including braided channels). Beyond this KaSPAR will also provide data over a variety of vegetated and ice-covered regions and ultimately help maximize the science return from SWOT. Understanding the performance impact of vegetation in particular is highly important since the retrieval of water elevations in marshlands and flooded regions is a primary goal of SWOT.

1.1.2 Vegetation Effects

An important but yet uncharacterized issue is any performance impact vegetation cover (as a function of density and type) may have for wetlands and flooded terrain with regards to signal attenuation.

Vegetation present either at the perimeter of rivers, reservoirs or lakes, or contained within the water body (e.g. wetlands or flooded regions) can distort the signal from the water surface in two ways: first, if it happens to lie in the path between the antenna and the water surface, it will attenuate the return from the desired target. The attenuated signal will have a lower signal to noise ratio and will therefore present a higher level of random noise. However, this random noise will be unbiased, and will not distort the estimation of the mean water level provided the dominant phase center is from the water surface. Due to the fact that the return is darker, water which lies below trees may be misclassified as land. If the attenuation, which we assume to be the exponential term $\exp[-\beta(T-z)/T]$ (where z is the height above the surface, and T is the tree height), is approximately equal to the intrinsic ratio between the vegetation return and the water return (μ), there will be confusion. Characterizing μ and β is important for understanding the limitations vegetation cover places on performance for various regions of interest for SWOT (eg regions of the Amazon basin, or ecologically important wetland and mangrove areas).

The second distortion due to vegetation is the fact that signals from the vegetation may arrive at the same time as signals from the water, an effect called layover in radar remote sensing. Layover can occur when the vegetation is present further from the water point along the range direction and in a locus of heights z obeying the equation $z = x \sin\theta_i$, where x is the distance along the ground between the water under observation and the patch of vegetation, and θ_i is the local incidence angle. Although for any suborbital sensor, as proposed here, the geometry will differ limiting direct measurement of layover effects, supporting measurements could be synthesized into a simulation such as that described by Durand et.al. [2008] to predict the impact.

Note that the NASA airborne Ka-band scanning radar altimeter [Walsh, 1998] capable of near-nadir angular discrimination of σ^0 rolloff is no longer in operation and that system was not capable of making temporal coherence measurements.

1.2 Swath Elevation Maps for Pre-mission Science and Mission Calibration/Validation

KaSPAR will also provide surface elevation swath-mapping for science algorithm development pre-mission and mission calibration and validation. This is represented by the wider illuminated region in Figure 1 and overlaps the narrow "SWOT-like" swath. Note that both swaths are collected together. For the ocean, at 35kft flight altitude the swath will be approximately 5km[1]. This capability is key to the relevance of KaSPAR for pre-mission science and also mission calibration and validation.

Calibration and validation of previous and current altimeter missions (Jason, Topex/Poseidon, OSTM) have relied on a series of calibration sites distributed globally (Bass Strait, Australia; Corsica France; Gavdos, Greece; Harvest Platform, USA and Ibiza, Spain). These locations use tide gauges and other sensors located directly under the satellite track. These observations have also been augmented during dedicated campaigns during the validation phase (http://www.aviso.oceanobs.com/en/calval/in-situ-dedicated-sites-and-campaigns/index.html). Similar observations and activities will be key and necessary components of calibration and validation for SWOT. However there are some additional challenges for calibrating SWOT:

1. There will be a need for land hydrology calibration and validation.
2. The swath-mapping and high resolution capability of KaRIN creates a new set of calibration and validation requirements.

KaSPAR will be an essential element of SWOT calibration and validation because it provides a spatial translation to tie the point-measurements to the space-borne swath. For example, gauges along a river network can provide estimates of slope between the disparate gauges. KaSPAR then, can provide slope variability between the gauges in the same manner as KaRIN but at higher resolution. Specific validation measurements from KaSPAR are:

1. height, h
2. slope (2-dimensional)
3. temporal change, dh/dt
4. shoreline delineation

Each of these measurements will be made at resolutions exceeding that of KaRIN, creating the ability to better characterize corrections or limitations for the spaceborne sensor. The 5km swath will enable mapping of entire river-basins in a reasonable time-frame. Furthermore, this swath will enable mapping of coastal eddy features and enable the generation of SWOT-like science products and observations for pre-mission algorithm development. Finally and importantly, the swath data can be used to verify critical calibration algorithms for SWOT.

KaSPAR data can also be used to augment SWOT in several ways:

1. KaSPAR will be capable of rapid response to fill temporal gaps between SWOT overpasses for critical events such as floods.
2. KaSPAR could be used to map finer-scale features that KaRIN cannot resolve such as smaller tributary rivers in strategic study areas.
3. Within the 5km swath, KaSPAR will not only provide elevation mapping, but an additional antenna displaced along-track will be used to provide radial velocity information about the surface. This measurement, can be used as a supporting measurement when evaluating discharge estimation algorithms [Bjerklie et. al., 2003].

[1] with a mean elevation accuracy of 2cm for a 50m x 80m posting and assuming a 6m/s wind. Higher elevations will generally yield more swath – details in Section 3.

4. Similar to SWOT, KaSPAR will also map surrounding terrain and could be used to build up detailed floodplain maps (for example).

2 Requirements

2.1 Near-nadir System Requirements to Mimic and Characterize SWOT

A key requirement is to mimic the SWOT sampling geometry. Generally the objective is to provide more measurements and detail so that there is additional information for analyzing the results and applying the interpretation to predict KaRIN’s performance. This levies the following requirements on the near-nadir sub-swath:

1. An elevation baseline should approximate the phase wrap-rate of SWOT. For approximate range of airborne altitudes this results in a cross-track baseline $0.16m<B<0.3m$.
2. The bandwidth should be greater than or equal to SWOT (>200MHz)
3. The minimum range of incidence angles should be similar to SWOT where $1^o<\theta_i<6^o$.
4. The height accuracies for the sub-swath should be similar to SWOT at a higher spatial resolution (as scaled to the airborne swath).
5. Additional supporting measurements of temporal coherence time are required to characterize along-track resolution limitations.
6. A system dynamic range equal to or greater than SWOT (> 40 dB).

2.2 Swath Elevation Mapping Requirement

The second system requirement is to provide swath elevation mapping capability for sample science products and KaRIN calibration and validation. The following is required for the swath product:

1. A swath of 5km over the ocean at 35kft altitude and 6m/s wind or greater.
2. Mean height precision of 2.5 cm for 50m range x 80m azimuth (as limited by the surface decorrelation with 6m/s wind) posting.

3 Proposed Solution

Our solution is an all solid-state modular radar system with multiple elevation and temporal interferometric baselines. The fundamental elevation baseline is chosen to replicate the SWOT geometries, but additional longer baselines are achieved through additional antennas and the capability to ping-pong. The longer baselines can be used for improved height precision and the combination of baselines can assist with unwrapping and elevation reconstruction.

The temporal baselines are chosen to characterize the range of decorrelation times expected, and at the outer (mapping) incidence angles provide radial velocity measurements of the surface.

3.1 Swath Mapping Performance

Table 1 summarizes the error sources assumed in predicting KaSPAR's elevation mapping performance, both near-nadir and for the mapping swath. For random error sources we have considered the signal-to-noise-ratio (SNR), geometric decorrelation and "zero-range" ambiguity explicitly (zero-range ambiguity is the uncorrelated return from the opposite side of nadir that will contaminate the height error). Other terms such as azimuth and range ambiguities, amplifier jitter, filter ripple etc have been conservatively lumped into the integrated sidelobe ratio (ISLR) and multiplicative noise ratio (MNR) term of -13dB.

For systematic errors we have considered three terms as the dominant (non-platform) sources:

1. Baseline dilation – the 20 microns allocation is derived from the panel design for the GLISTIN IPY system which we would hope to leverage for this effort.
2. Receiver phase-drift *knowledge* of 0.2^{o} (over 10 minutes) is challenging but achievable [Vedantham et. al. 2008] with careful design and thermal packaging.
3. Range-timing accuracy

The elevation performance for the near-nadir "SWOT" sub swath is shown in Figure 2. The solid lines show the performance for the SWOT-like baseline, and the dashed line are for a longer baseline combination. At the higher accuracy just under 2cm mean *accuracy is achieved with no additional calibration for the systematic errors.*

For the near-nadir, or "inner" sub swath, the combination of short and long baselines coupled with a high bandwidth will enable a systematic assessment of phase-unwrapping limitations (over floodplain terrain for example) that KaRIN might encounter.

Table 1: Error sources and allocations assumed in predicting the elevation accuracy of KaSPAR The performance quoted for the inner swath assumes no calibration of systematic biases and a 20m range posting. For the outer-swath – the performance assumes a nadir altimeter for (using existing KaSPAR hardware) and a 50m range posting**.**

Error Source		**Quantity**	**Unit**
Random	SNR	Derived from system radar-range equation for ocean at 6m/s wind	Unitless ratio
	Geometric	Derived for each baseline	
	ISLR/MNR	-13	dB
	Zero-range ambiguity	Relative gain of 2-way antenna pattern from opposite side	Unitless ratio
Systematic	Receiver phase-drift *knowledge* error	0.2	°
	Baseline dilation	20	microns
	Range-timing accuracy	3	ns
Mean Height Error Performance (35kft, 6m/s winds over ocean)			
Inner subswath		1.8	cm
Outer swath		2.3 [2]	cm

[2] Calculated as the root sum square of the residual calibration error (1 cm) and the random errors.

Figure 3 shows the elevation mapping performance for the mapping swath. Again we show a series of solid lines for the minimum baseline, and then dashed lines for the long baseline in ping-pong mode (or the highest precision mode). Because the maximum cross-track extent is significant for the outer swath the systematic errors present a significant impact on the height-errors. The result is the error rollup exceeds our requirements for a useful calibration/validation sensor. However, even if the system design could be improved to further reduce the systematic biases, the height sensitivity to aircraft roll knowledge (not explicitly budgeted here) is too great even with state-of-the-art technology to meet the requirement goal. Therefore we concluded that the only realistic way to reach the centimetric accuracy desired is with a data calibration approach.

The calibration strategy we will use employs traditional waveform tracking techniques for a nadir "altimeter" mode. This can be achieved using the existing antennas. Because in altimeter mode we are tracking the nadir return, the altimeter-processed data is very insensitive to roll errors (i.e. both the "effective" roll due to systematic errors and actual roll errors due to aircraft motion). Thus the nadir profile can be used as our calibration "truth". As swaths are flown to map say, an eddy region, or a river basin, the flight-plan must overlap the far-swath with the nadir profile from successive or prior tracks. In this manner, the nadir profile can be used to correct the far-swath of the overlapping line. The underlying assumption is that the height of the ocean features (e.g. eddies) or river/lakes being measured do not significantly change within the time elapsed between successive passes. The measurement interval can be assumed to be tens of minutes, while the processes of interest are dynamic on the time scales of hours to days and weeks making this assumption more than reasonable.

Referring back to Figure 3, and assuming the nadir track is used to correct for systematic errors, the underlying performance of KaSPAR for elevation mapping is given by the root-sum-square of the blue random-height error curves and a residual calibration error (assume 1cm). The average performance across the swath is then 2.3cm for the longest baseline in ping-pong mode.

Figure 4 shows the horizontal velocity performance for the along-track baseline. Note that the performance worsens dramatically toward nadir since the horizontal projection of the viewing geometry becomes very small. Beyond 5^{o} incidence however the precision is very good at just a few cm/sec (we have assumed the same posting of 50m range as for the elevation mapping). The unambiguous velocity is approximately +/-5ms^{-1} so unwrapping should not be necessary. Absolute calibration can be achieved by using known stationary targets (land). Although this measurement is of the radial component of the velocity only, reasonable assumptions about the general direction of flow (i.e. for rivers as done by [Bjerklie et. al. 2003]) or flying crossing paths if desired can help resolve a vector if necessary.

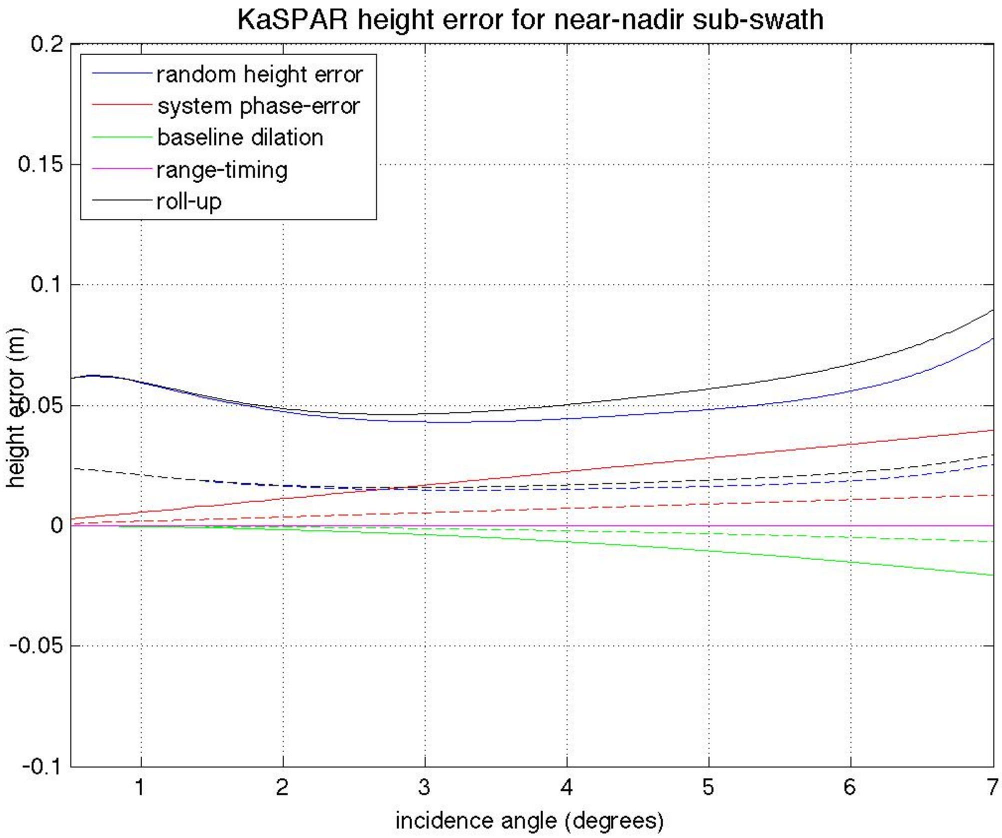

Figure 2: Elevation accuracy of the inner subswath. The solid lines are for the short "SWOT-like" elevation baseline, while the dashed line are for the longer cross-track baseline. The posting is 20m in range, but ~80m along-track as limited by the ~3ms decorrelation time assumed for a 6m/s wind.

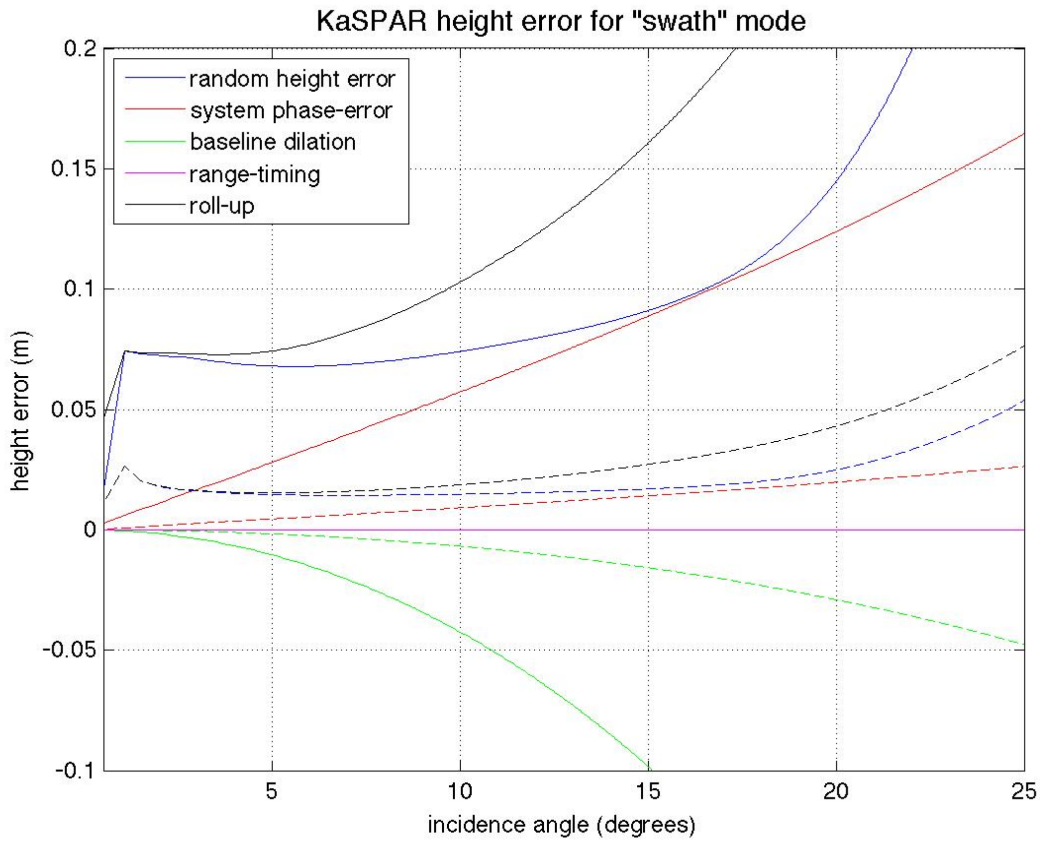

Figure 3: Elevation accuracy of the inner subswath. The solid lines are for the short "SWOT-like" elevation baseline, while the dashed line are for the longer cross-track baseline and assume ping-pong. The posting is 50m in range, but ~80m along-track as limited by the ~3ms decorrelation. In order to meet requirements a nadir altimeter mode is necessary to correct the systematic biases.

4 Aircraft Compatibility & Considerations

To meet the elevation accuracy requirement without using electronic beam steering, the altitude must be increased and the transmitted bandwidth must be decreased. Decreasing the transmitted bandwidth in the outer swath will not cause a large impact because the ground resolution will still be comparable to that of the inner swath. Therefore our initial focus was to look at the altitude trade. We have assessed a range of candidates primarily from the NASA Airborne Sciences program that operate from a variety of NASA centers. One of the key criteria for aircraft candidacy is altitude of operation because we can achieve our swath over a narrower range of incidence angles where the σ_0 is brighter as we go up in altitude. Figure 5 plots, as a function of altitude, the outer incidence angle required to achieve a 5 km swath. For the P-3 (25kft) and C-130 (30kft) aircraft, the KaSPAR system would be required to collect measurements out to 30 degrees incidence in order to achieve the 5 km swath. The σ_0 at these angles is much too low under most conditions. Other options include deployment on the King Air (32-35 kft), Gulfstream aircraft (40-45 kft) or high altitude aircraft, such as the Global Hawk (65 kft). Although the final goal is to be capable of flying on the Global Hawk UAV, programmatically and practically it is necessary that KaSPAR be operational from a manned aircraft, while still meeting the measurement requirements for a SWOT-like configuration. From this analysis, the King Air probably offers the best trade-offs. At 35 kft altitude, KaSPAR would only require measurements to approximately 25 degrees incidence to achieve the 5 km swath.

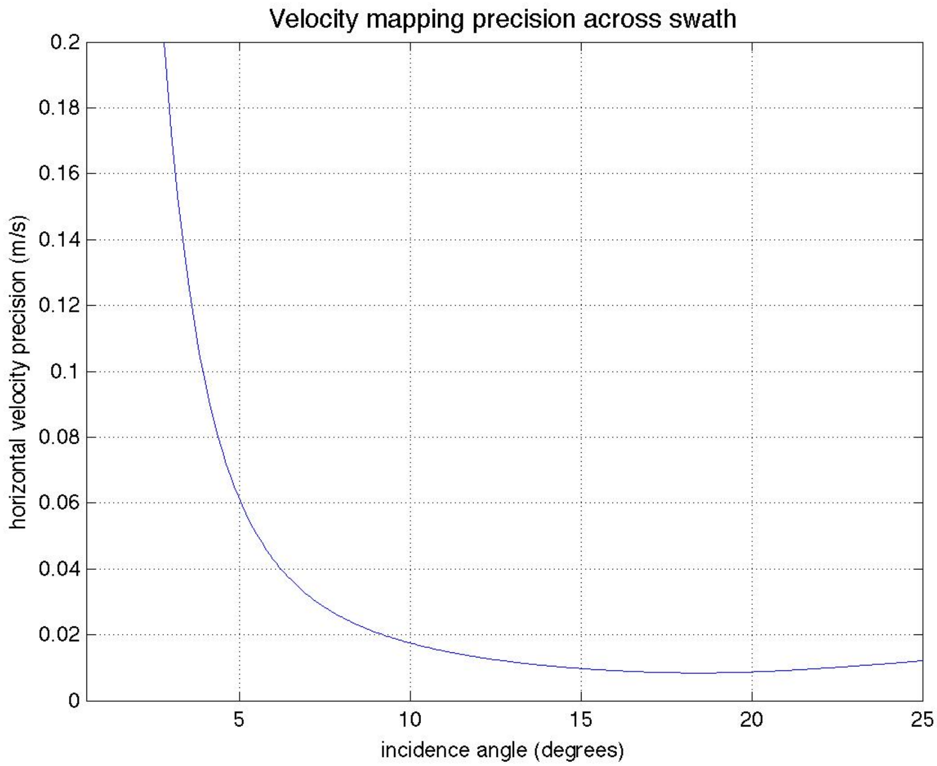

Figure 4: Radial velocity performance across swath. As a supporting measurement the velocity can be used in conjunction with slope in discharge estimation for example, or give supporting hydraulics information. The radial component only is measured. The posting is 50m in range, but ~80m along-track as limited by the ~3ms decorrelation.

Further assessment of the King Air is very encouraging. The NASA Langley King Air has two large nadir viewing ports, the larger of which should be able to accommodate the antenna panel installation. Recently NASA Dryden Flight Research Center has modified a King Air B200 replicate the Langley nadir port configuration. Both these aircraft have a 35kft ceiling.

5 KaSPAR Applications

Designed to support SWOT, KaSPAR provides unique measurement capabilities that will enhance interpretation of SWOT measurements, validate and improve SWOT products, extend SWOT applications and provide complimentary high resolution measurements to SWOT observations. As such, KaSPAR is envisioned to play a significant role in pre-launch and post-launch SWOT calibration and validation activities and take part in future SWOT science field campaigns.

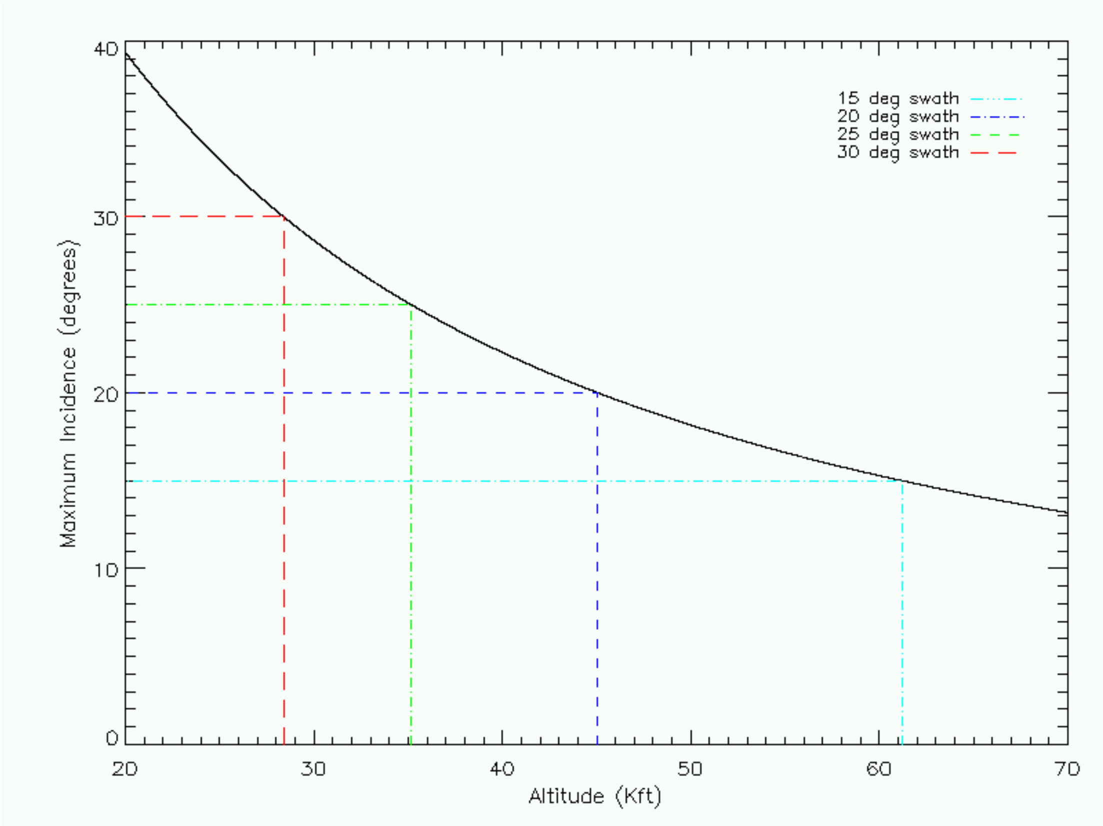

Figure 2: Trade of aircraft altitude versus incidence angle to meet a 5km swath. Because the scattering cross-section of water falls off quickly at large incidence angles, there is a distinct advantage to higher operational elevations**.**

The KaSPAR and its technology also fill technology gaps that exist in several other commercial and governmental applications. A summary of a few potential applications are described below.

5.1 River Discharge and Flood Stage

Recent work has shown that the velocity width of a river can be used to relate its discharge rate to stage level. US Coast Guard and USGS have expressed interest in using KaSPAR to build such a data base for high use (recreational and navigation) rivers. This would improve the performance of models used to predict discharge rate and flow patterns of rivers that use stage level data from in situ river gauges, and in the future, from SWOT elevation. In turn, this would aid navigation and would provide critical information to search and rescue operations. KaSPAR could also be deployed rapidly to provide measurements that are needed urgently and in specific locations where SWOT data may not be available in a timely manner or cannot resolve the rivers features due to resolution limitations.

5.2 Weather Reconnaissance and Flooding

Prior to landfalling ocean storms that threaten populated areas, a KaSPAR system could be flown to provide spatial measurements of the storm surge that may threaten these areas. As the storm makes landfall and passes, a KaSPAR could be deployed to map the flood state over large regions when such information is time critical.

5.3 Inland Water Bodies

In discussions with navigational companies, such as C-Map, many inland water bodies (e.g. small lakes and ponds) have not been accurately mapped, yet many recreational and sporting boaters use these waters. Airborne lidar technology is often used to provide data on these smaller water bodies, but because of limited swath, obtaining the required data is expensive. A KaSPAR system provides significantly more coverage in a single pass making it more practical and cost effective for mapping these water bodies.

5.4 Electronic Vision

Ka-band interferometry has potential to provide 3D mapping of scenes during limited low visibility conditions (i.e. fog, drizzle, etc). The technology developed for KaSPAR may be used to realize Ka-band radar interferometer electronic vision systems that would complement existing infrared systems. The aircraft industry has expressed significant interest in this area.

5.5 Mapping

Although designed for mapping rivers and oceans, a KaSPAR system could be used to provide 3D terrestrial imaging. Such data would be of interest to many industries from those involved with providing topography data sets to local and national governments requiring such information for emergency planning to land management to resource monitoring. Service providers, such as Google, may also be interested in these data to distinguish their products and enable new applications.

7 Conclusions

In this white paper we have presented a concept and performance for an airborne sensor, motivated in support of SWOT pre-mission and mission needs. The design incorporates multiple baselines in a modular and compact architecture for maximal versatility in terms of measurement capabilities and also multiple platform compatibility. The design presented has the potential to greatly enhance SWOT science return on investment. Key subsystems of KaSPAR are currently under development funded by a Phase II NASA SBIR.

References

[Alsdorf et. al. 2007a] D. Alsdorf, Feu L. L, N. Mognard, A. Cazenave, E. Rodriguez, D. Chelton, D. Lettenmaier, Measuring Global Oceans and Terrestrial Freshwater From Space, *EOS Transactions*, American Geophysical Union, no. 24, pp. 25, 2007

[Alsdorf et.al. 2007b] D. Alsdorf, E. Rodriguez, and D. P. Lettenmaier, Measuring surface water from space, Rev. Geophys., 45, RG2002 doi:10.1029/2006RG000197.

[Anthes and Moore, 2007] R.A. Anthes, and B. Moore (eds.), Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond, Committee on Earth Science and Applications from Space: A Community Assessment and Strategy for the Future, National Research Council, ISBN: 0-309-66714-3, 456 pages, http://www.nap.edu/ catalog/11820.html, 2007.

[Birkett et. al. 2002] C.M.Birkett, L.A.K. Mertes, T. Dunne, M.H. Costa, and M.J. Jasinski, Surface water dynamics in the Amazon Basin: Application of satellite radar altimetry, *Journal of Geophysical Research, 107*, 10.1029/2001JD000609, 2002.

[Birkett 1998] C.M. Birkett, Contribution of the TOPEX NASA radar altimeter to the global monitoring of large rivers and wetlands, *Water Resources Research, 34*, 1223-1239, 1998.

[Birkett 1995] C.M. Birkett, The contribution of TOPEX/POSEIDON to the global monitoring of climatically sensitive lakes, *J. Geophysical Res., 100*, 25179-25204, 1995.

[Bjerklie et.al., 2003] D. Bjerklie, D.Moller, L.Smith, S.L.Dingman, Estimating Discharge in Rivers Using Remotely Sensed Hydraulic Information, *Journal of Hydrology*, 309, pp 191-209, 2003.

[Carande 1994] R.E. Carande, Estimating ocean coherence time using dual-baseline interferometric synthetic aperture radar. *IEEE Transactions on Geoscience and Remote Sensing*, 32, 4 (July 1994), 846–854.

[Durand et.al 2008] M. Durand, K.M. Andreadis, D.E. Alsdorf, D.P. Lettenmaier, D. Moller, and M. Wilson, Estimation of bathymetric depth and slope from data assimilation of swath altimetry into a hydrodynamic model, *Geophysical Research Letters*, v.35, L20401, doi:10.1029/2008GL034150, 2008.

[Fu and Cazenave, 2001] L. L. Fu, A. Cazenave Eds., Altimetry and Earth Science, A Handbook of Techniques and Applications, vol. 69 of International Geophysics Series, Academic Press, London, 2001

[Moller and Rodriguez, 2007] D. Moller and E. Rodriguez, Near-nadir Ka-band radar backscattering statistics for surface water interferometric altimetry, Research and Technology Development Final Report, http://rtd/reports/rtd07/report.html, Jet Propulsion Laboratory, 2007

[Moller, 2009] D. Moller, GLISTIN NASA Airborne Science Quarterly Report, June, 2009.

[Tanelli et. al. 2006] S. Tanelli, S.L. Durden, E. Im., Simultaneous measurements of ku- and ka-band sea surface cross sections by an airborne Radar, *Geoscience and Remote Sensing Letters*, IEEE. 01/08/2006; 3(3):359- 363. DOI: 10.1109/LGRS.2006.872929, 2006

[Vandemark et. al., 2004] D. Vandemark, B. Chapron, J. Sun, G.H. Crescenti and H.C. Graber, Ocean wave slope observations using radar backscatter and laser altimeters, *J. Physical Oceanography*, vol. 34, 2825-2842, Dec. 2004.

[Vedantham et. al. 2008] H. Vedantham, P. R. Siqueira, K. Srinivasan, E. Insanic, A Ka-Band Interferometer For Cryospheric Applications - Instrument Description And First Results, Proc. IGARSS 2008

[Walsh et.al 1998] E.J.Walsh, D. C. Vandemark, C. A. Friehe, S. P. Burns, D. Khelif, R. N. Swift, and J. F. Scott, Measuring sea surface mean square slope with a 36-GHz scanning radar altimeter, *J. Geophys. Res.*, vol. 103-C6, pp. 12.587–12.601, 1998.

[Walsh et. al. 2008] E.J. Walsh, C.W. Wright, M.L. Banner, D.C. Vandemark, B. Chapron, J. Jensen and S. Lee, The southern ocean waves experiment. Part III: Sea surface slope statistics and near-nadir remote sensing, *J. of Physical Oceanograpy*, Vol. 28, No 3. 670-685, March 2008.