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QuikSCAT Follow-On Concept Study

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Abstract

Global, real-time observations of the speed and direction of winds over the oceans (ocean surface vector winds [OSVW]) are high priority measurements for National Oceanic and Atmospheric Administration's (NOAA's) weather forecasting, prediction, and hazard warning communities. At present, these data are provided by the experimental National Aeronautics and Space Administration (NASA) QuikSCAT satellite sensor, which is operating well beyond its design lifetime. To continue to meet the Nation's need for operational OSVW observations beyond QuikSCAT, NOAA tasked the Jet Propulsion Laboratory (JPL) to design and provide costs for a set of QuikSCAT Follow-On mission options. Three scenarios were examined: 1) a QuikSCAT Replacement mission with capabilities commensurate to QuikSCAT, 2) a next-generation Extended Ocean Vector Winds Mission (XOVWM), as recommended in the National Research Council's decadal survey to provide significantly improved all-weather, all-wind, high spatial resolution measurements, and 3) an XOVWM Constellation consisting of two XOVWM observatories to provide improved temporal resolution. In parallel, NOAA asked its users to provide a quantitative assessment of each option's benefit to NOAA. This report presents the JPL design, risk assessment, and cost for each of three options, together with a summary of the NOAA users' benefit assessment. The report concludes that though all options are technically feasible for immediate implementation and have a risk posture consistent with a NOAA operational mission, the XOVWM options provide significant observational benefits. While a QuikSCAT Replacement option would continue current operational measurement capabilities, there is a strong and clearly defined operational need for improved capabilities in high winds (e.g., hurricanes or extra-tropical cyclones), heavy precipitation, and near coasts to enable significantly improved severe storm and coastal hazard forecasts, which are provided only by the XOVWM options.

Executive Summary

The benefits of measuring surface vector winds over the ocean are widely recognized [1]. Monitoring these winds is essential to operational weather forecasting, hurricane and extra-tropical cyclone monitoring, shipping safety, fisheries, and a host of other applications crucial for the operational and scientific understanding of the interaction between the atmosphere and the ocean.

In the past decade, the National Aeronautics and Space Administration (NASA) QuikSCAT scatterometer satellite, which launched in 1999, has provided NASA and NOAA with a proven method for monitoring ocean surface vector winds (OSVW) from space, and its data have become integral to National Oceanic and Atmospheric Administration's (NOAA's) weather forecasting capabilities [2]. The need to continue and improve upon these monitoring capabilities, beyond the lifetime of QuikSCAT, was identified by the National Research Council (NRC) in its recent *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond* [1], which recommended development of a next-generation Extended Ocean Vector Winds Mission (XOVWM) to improve upon QuikSCAT's capabilities to meet the full needs of NOAA's users [2]. The XOVWM capabilities relative to QuikSCAT are shown in Figure 1.

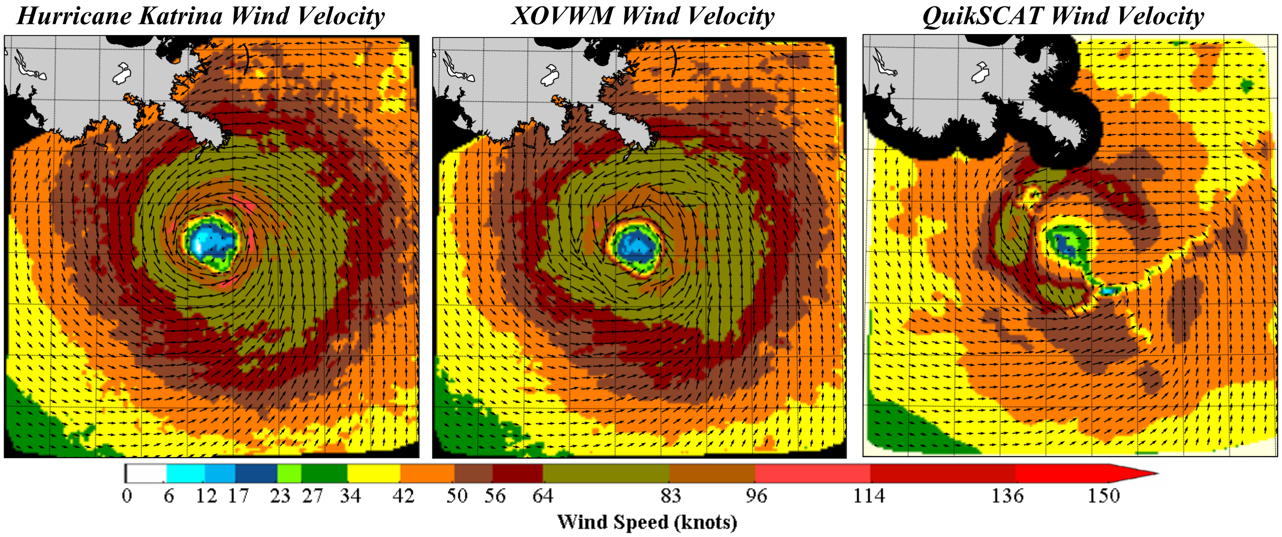

Figure 1: *Comparison of realistic hurricane ocean surface vector winds (left) with data that would be produced by a single XOVWM (center) and QuikSCAT (right). Note that while XOVWM correctly reproduces all major aspects of the hurricane, QuikSCAT underestimates wind velocities, misplaces the hurricane center, and lacks data near the Louisiana coast.*

To understand the relative merits of different options for meeting its ocean surface vector winds requirements, NOAA tasked the Jet Propulsion Laboratory (JPL), the developers of the QuikSCAT mission, to perform technical and cost assessments of three mission scenarios (depicted in Figure 2), which trade cost and risk against measurement capability. In parallel with this effort, a team of NOAA users provided an assessment of each option's value to NOAA [3]. The three options studied were:

1. **QuikSCAT Replacement**: This option implements a mission functionally equivalent to QuikSCAT. A new instrument architecture was developed to accommodate parts obsolescence considerations and to allow for future upgraded capabilities.
2. **XOVWM**: This option implements a next-generation XOVWM as recommended by the NRC decadal survey to provide all-weather, all-wind, high spatial resolution measurement capability to enable significantly improved severe storm and coastal hazard forecasts.

3. **XOVWM Constellation**: This option examines the long-term cost advantages of flying two XOVWM spacecraft in formation to improve the revisit time of the measurements, which is desired for optimal tracking of fast moving weather events, such as hurricanes or extra-tropical cyclones. This solution best meets NOAA user needs, and is viewed as the ideal long-term operational scenario.

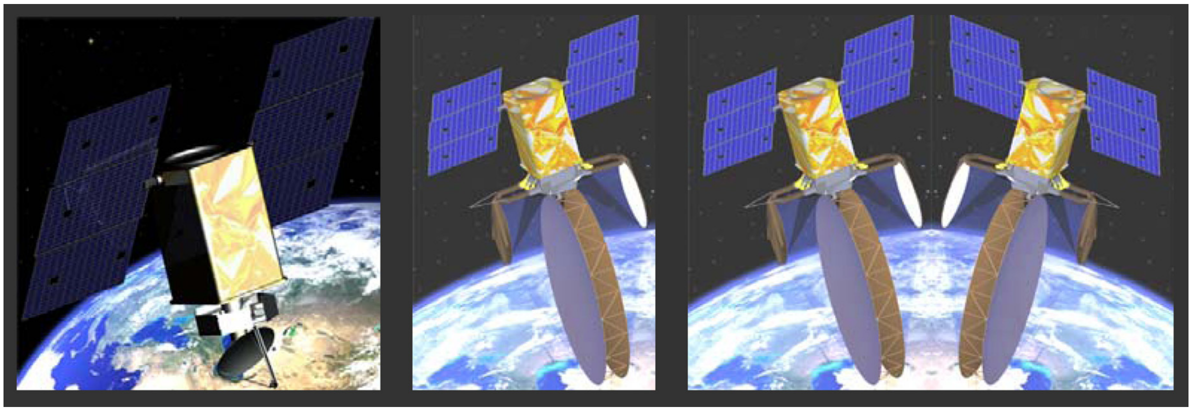

Figure 2: *(a) QuickScat Replacement* *(b) XOVWM* *(c) XOVWM Constellation*

The NOAA user evaluations have been compiled into a user impact study [3], which complements the results presented here. The user impact study provides detailed assessments of the many significant benefits of scatterometry measurements to NOAA operations, and includes evaluations by key NOAA national centers (the Ocean Prediction Center [OPC], the Tropical Prediction Center/National Hurricane Center [TPC/NHC], the National Ice Center [NIC], and the Central Pacific Hurricane Center), all of the Regional Weather Forecasting Offices, and the Atlantic Oceanographic and Meteorological Laboratory. Three critical conclusions can be extracted [3]:

1. “[...]in order to sustain the improvements in the operational weather forecasting and warning program that result from the availability of QuikSCAT data, all NWS users have set the QuikSCAT-equivalent capability as a minimum or threshold OSVW capability.”
2. “An XOVWM capability would yield significant benefits over a QuikSCAT equivalent capability in: Extratropical cyclones [...]; Tropical cyclones [...]; Coastal regions and Great Lakes[...]. An XOVWM OSVW mission would significantly advance the improvements in operational weather and forecasting capabilities that are realized today, and would better address the satellite OSVW requirements for operational weather forecasting and warning.”
3. “From all inputs received from NWS forecast offices and centers, the most significant conclusion is that even a single XOVWM would be a major step toward meeting critical aspects of OSVW operational requirements compared to a QuikSCAT-equivalent solution.”

In addition to the efforts undertaken to support the NOAA user community assessment, the study included significant design development for the XOVWM options in order to provide a credible risk assessment and cost estimate. The XOVWM design was initiated at JPL under funding provided by NASA, and instrument designs were reviewed in May 2007 by a panel of experts that included engineers and scientists from JPL, NOAA, academia, and industry. The review panel endorsed the instrument design approach and provided feedback on ways to prove feasibility, mature the design, and further reduce risk. Under this present study for NOAA, JPL has addressed the issues raised by the review panel and has identified solutions for all of them. Sufficiently detailed instrument design, analysis, risk assessments, and testing have now been performed to assert that the design is consistent with that required at mission start (Phase A), and no new technology development is required beyond the engineering development process typical for NOAA operational space missions.

The study also examined the availability of spacecraft buses with heritage suitable for accommodating the XOVWM or QuikSCAT Replacement payloads. A Request for Information (RFI) was released to industry soliciting data on the feasibility of accommodating these payloads given instrument requirements, including mass, power, orbit, stability, and data rate. Four major aerospace firms submitted detailed responses. Although aspects of the proposed solutions differed, all responses agreed that both XOVWM and the QuikSCAT Replacement options could be accommodated with relatively minor modifications to existing mature spacecraft buses.

Detailed grass-roots cost estimates were developed for each of the three follow-on mission options. The resulting costs were reviewed by the management of each of the JPL technical organizations involved, and validated at a cost review with independent technical experts, JPL upper management, and NOAA and NASA participants. See Table 1 for costs in fiscal year 2008 (FY08) dollars, and refer to Section 8.5 below for funding profiles in real year dollars.

To further validate the cost estimate, an independent cost estimate (ICE) was prepared by the Aerospace Corporation, based on scaled analogies with previous missions and parametric cost models. The results of the ICE are within 4% of the grass-roots costs for a 70th percentile estimate, giving confidence that the rough-order-of-magnitude (ROM) cost estimates are reasonable and appropriate for budget planning purposes for a new mission start.

Table 1: *Cost comparison (in FY08 fixed-year dollars) of QuikSCAT Replacement, XOVWM, and XOVWM Constellation (excludes costs associated with NOAA organizational responsibilities, in Section 8.2)*[*]

	Options (FY08 $M)		
	1	**2**	**3**
Cost Element	**QuikSCAT Replacement**	**XOVWM**	**XOVWM 2 S/C Constellation**
Phases A–D			
Management, System Engineering, & Mission Assurance	$30.1	$34.5	$40.8
Science	$4.7	$7.3	$8.5
Payload	$91.6	$161.1	$208.8
Spacecraft Bus	$86.8	$91.4	$142.1
Mission Operations	$3.3	$4.4	$5.0
Data Processing System	$5.6	$13.5	$13.8
Subtotal	$222.1	$312.2	$419.0
Reserve	$66.2	$92.0	$125.9
Phase A–D Subtotal	**$288.3**	**$404.2**	**$544.9**
Phase E			
On-Orbit Calibration/Validation	$2.8	$3.5	$4.6
Mission Operations	$9.4	$10.6	$13.2
Subtotal	$12.2	$14.1	$17.8
Reserve	$1.8	$2.1	$2.7
Phase E Subtotal	**$14.0**	**$16.2**	**$20.5**
Launch Vehicle	$32.0	$77.0	$154.0
Other NASA Costs	$1.9	$2.4	$3.3
JPL Total	**$336.2**	**$499.8**	**$722.7**

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[*] The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

Summary, Conclusions, and Recommendations

Three mission options for continued provision of operational ocean surface vector winds data (QuikSCAT Replacement, XOVWM, and XOVWM Constellation) were evaluated. All options are technically feasible. Detailed cost estimates have been developed and independently validated. While a QuikSCAT Replacement option would continue current operational measurement capabilities, there is a strong and clearly defined operational need for improved capabilities in high winds (e.g., hurricanes or extra-tropical cyclones), heavy precipitation, and near coasts to enable significantly improved severe storm and coastal hazard forecasts, which are provided only by the XOVWM options.

The NOAA user impact study unambiguously recommends proceeding with a XOVWM mission start as soon as feasible. The XOVWM mission concept is mature, uses existing technology, and is ready for an immediate Phase A mission start to support operations as early as the 2013 hurricane season, depending on funding availability.

Section 1: Background & Requirements for Ocean Vector Winds Measurement

The need for continued ocean surface vector winds scatterometer measurements is clear and well-documented. National Oceanic and Atmospheric Administration (NOAA) users have identified critical improvements required over current operational capabilities to meet NOAA's long term needs, which can only be met by a next-generation active scatterometry system. Options for both measurement continuity and improvement have been studied, and the measurement performance associated with each option is described here.

1.1 Requirements for Ocean Vector Winds Data

The NOAA user community has a long history of using radar scatterometer derived ocean surface vector winds (OSVW) measurements, and measurements from the QuikSCAT scatterometer are currently used operationally by NOAA weather forecasters and modelers. NOAA convened a user workshop in June 2006 at the Tropical Prediction Center/National Hurricane Center (TPC/NHC) to assess the need for continued scatterometer OSVW measurements and to derive the long-term NOAA requirements. This workshop, hereafter referred to as the "NOAA ocean winds workshop" resulted in a workshop report [2], which can be obtained at http://manati.orbit.nesdis.noaa.gov/SVW_nextgen/.

The NOAA ocean winds workshop [2] clearly established the need for continued OSVW scatterometer measurements and documented the many benefits that have resulted from the use of QuikSCAT data. However, the NOAA users were also clear that, in order to meet NOAA's long-term needs, a significant increase in OSVW measurement capabilities is required. Three major issues were identified as needed improvements to the QuikSCAT performance:

1. **All-Wind Measurement Capabilities:** *The NOAA users recommended that the next-generation system be able to measure the entire range of wind speeds up to those expected in hurricanes.* For hurricanes, NOAA is required to report wind speed radii for 34-kt, 50-kt, and 64-kt winds. Category 1 hurricane winds start at 64 kts, and category 5 winds start at 150 kts. High wind speeds cannot be reliably measured by QuikSCAT, due to its exclusive use of Ku-band frequency. The NOAA users have found that QuikSCAT data can only be used to predict 34-kt wind radii reliably (see Figure 4).
2. **All-Weather Measurement Capabilities:** *The NOAA users recommended that the next-generation system be able to measure winds even in hurricane conditions.* While QuikSCAT can operate successfully under cloudy and light-rain conditions, it is severely limited in the heavy rain conditions found in tropical cyclones (see Figures 4 and 5). For extra-tropical cyclones, critical to North-Atlantic shipping, rain contamination is smaller, but rain artifacts can still be observed.
3. **Higher Spatial Resolution:** *The NOAA users recommended that the spatial resolution of the next-generation system be substantially improved so that kilometer-level phenomena could be resolved.* Due to its large footprint, QuikSCAT has limited spatial resolution, which prevents retrieval of winds within 20 km of the coast, where the bulk of shipping lanes and fishing occurs. This limits the usefulness of QuikSCAT data for forecasting wave and wind hazards affecting coastal communities. QuikSCAT's limited spatial resolution also hampers its ability to resolve high winds for both tropical and extra-tropical cyclones. Higher spatial resolution is desired to reduce these limitations.

The National Research Council (NRC), in its decadal survey report, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond* [1], noted that these measurement enhancements would yield the following benefits:

1. Improved estimates of coastal upwelling and nutrient availability.
2. Improved estimates of the heat and carbon exchanges between the atmosphere and ocean.

3. Understanding of fisheries productivity sensitivity to nutrient availability.
4. Improved navigation safety.
5. Improved predictions of hurricanes, extra-tropical storms, coastal winds, and storm surges.

Using these user-desired measurement capabilities, Jet Propulsion Laboratory (JPL) and NOAA collaborated to develop a set of Level 1 requirements for the study's mission options. The requirements agreed to in Table 2 for Extended Ocean Vector Winds Mission (XOVWM) meet the NOAA user requirements with a cost-efficient, highly reliable instrument with mature technology. The QuikSCAT Replacement capabilities in Table 2 do not meet the user requirements, but do provide continuity of current capabilities. The XOVWM Level 1 mission requirements have been derived from the NOAA user requirements for improved OSVW data, whereas the QuikSCAT Replacement mission Level 1 capabilities are based on existing measurement capabilities (Table 2). The cases studied thus allow examination of the trade between continuing baseline current capabilities and satisfying the ultimate user requirements.

Table 2: *Level 1 requirements used for this study for QuikSCAT Replacement, XOVWM, and an XOVWM Constellation mission. The capabilities shown in green satisfy the user requirements.*

Requirement	User Requirements	1. QuikSCAT Replacement	2. XOVWM	3. XOVWM Constellation
Horizontal Resolution	<5 km	12.5 km	**<5 km**	**<5 km**
Coastal Mask	<5 km	20 km	**<5 km**	**<5 km**
Coverage	90% of the ocean surface every 24 hours	**90% of the ocean surface every 24 hours**	**90% of the ocean surface every 24 hours**	**90% of the ocean surface every 12 hours**
Wind Speed Accuracy (RMS)	3–20 m/s: 2 m/s 20–30 m/s: 10% 30–80 m/s: 10%	**3–20 m/s: 2 m/s** **20–30 m/s: 10%** 30–80 m/s: not specified	**3–20 m/s: 2 m/s** **20–30 m/s: 10%** **30–80 m/s: 10%**	**3–20 m/s: 2 m/s** **20–30 m/s: 10%** **30–80 m/s: 10%**
Wind Direction Accuracy (RMS)	3–30 m/s: 20° 30–80 m/s: 20°	**3-30 m/s: 20°** 30–80 m/s: no requirement	**3–30 m/s: 20°** **30–80 m/s: 20°**	**3–30 m/s: 20°** **30–80 m/s: 20°**
Retrieval in Precipitation	All-weather wind retrieval	None in heavy precipitation	**All-weather wind retrieval**	**All-weather wind retrieval**
Product Latency	< 180 minutes for 85% of the data	**< 180 minutes for 85% of the data**	**< 180 minutes for 85% of the data**	**< 180 minutes for 85% of the data**
Mission Design Life	n/a	**5 years (consumables for 10 years)**	**5 years (consumables for 10 years)**	**5 years (consumables for 10 years)**

NOTE: RMS = root mean square

The requirements have been briefed to a large group of NOAA users and, as a parallel part of this study, user assessments of the expected impact of missions designed to these requirements have been obtained. The result of this parallel study is presented in a complementary NOAA user impact study [3].

1.2 Instrument Measurement Performance

The performance characteristics of the QuikSCAT instrument, captured in Table 2, are well known [4], and serve as the Level 1 requirements for the QuikSCAT Replacement mission. To evaluate the performance of the proposed XOVWM mission presented in Section 4, existing simulation tools that had been developed for QuikSCAT were modified to enable simulation of instrument performance and wind retrievals for the XOVWM instrument. These modifications entailed adding the capability to simulate winds at high resolution for Ku- and C-bands and implementing the capability to do joint wind retrievals using these channels. Validation of the modified tools included demonstrating that unique features of

QuikSCAT data were reproduced by the simulations; forecasters at the NOAA Ocean Prediction Center (OPC), who use the real QuikSCAT data routinely, concurred that the simulations were consistent with the known behavior of QuikSCAT.

Given the scope of this study, the X-band radiometer channel was not modeled in detail and the joint retrieval algorithms for XOVWM have not been tuned to take full advantage of the additional frequencies. Thus, the excellent performance results presented below are expected to improve as the algorithm development activities proceed.

Figure 3 presents a global assessment of the accuracy of the XOVWM performance for all wind speeds covered by the Level 1 requirements up through 70 m/s. Performance for wind speeds above 70 m/s can be extrapolated from Figure 3, but because winds in that range are so rare, the model functions have not been formulated in that domain and accurate simulations are therefore not possible. These simulation results were obtained by synthesizing the desired wind fields (speed, direction, and resolution), simulating the resulting radar backscatter measurements, completing the wind estimation process, and comparing the results against the "truth" simulation values.

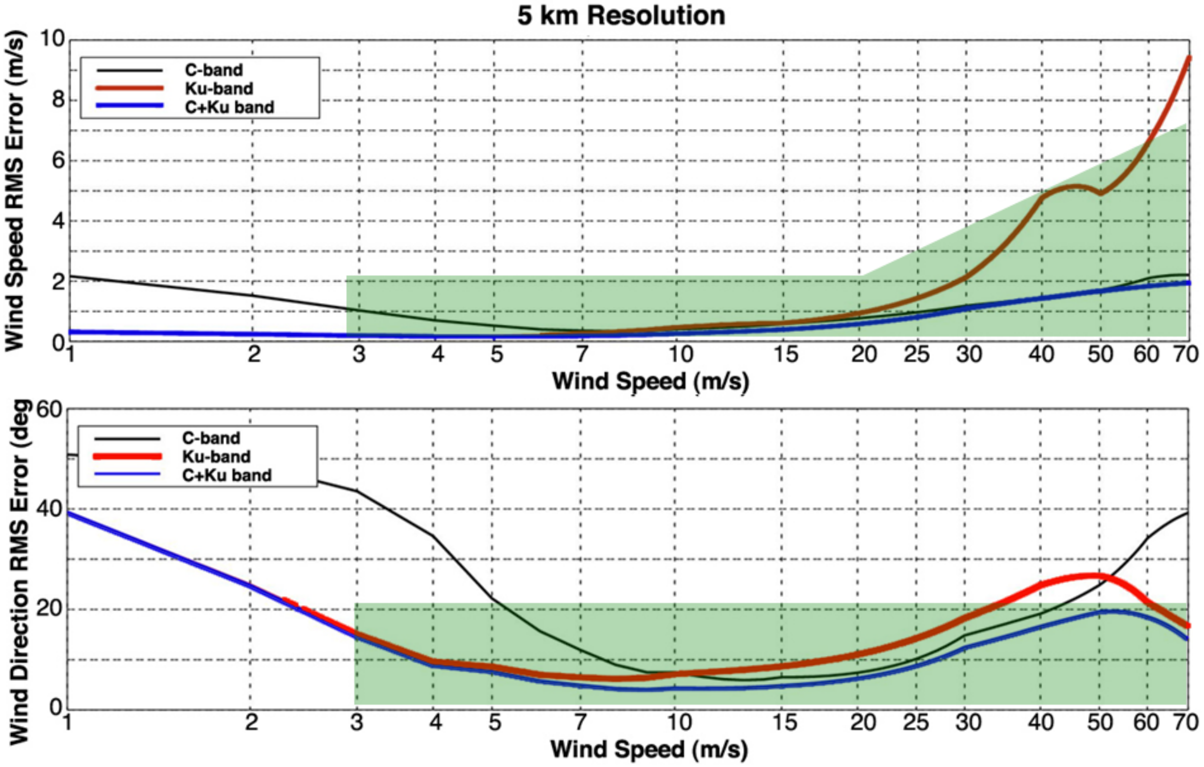

Figure 3: *Global performance of the XOVWM instrument in wind speed and direction. The green zones represent the Level 1 requirements in Table 2. The black lines correspond to the C-band channel performance; the red line, the Ku-band channel performance; and the blue line, the performance combined by retrieving winds using both channels simultaneously. Note that both channels are required to meet the requirements over all wind speed ranges. The retrievals were performed at 5-km resolution.*

As shown in Figure 3, it is not possible to meet the mission requirements using only a single frequency (e.g., by a QuikSCAT Replacement). However, by combining Ku- and C-band observations, as is done for XOVWM, the desired performance is met with margin for all wind speed ranges.

As a complement to this statistical assessment of XOVWM performance, we present below summaries of results for case studies that were selected by NOAA as being critical for the evaluation of XOVWM instrument performance. In this report, we only summarize the results of the user impact study and refer the reader to the NOAA report [3] for additional details.

1.2.1 Hurricanes

Hurricanes are a very important component of NOAA's weather forecasting mission, and a phenomenon where XOVWM can have a significant impact beyond that provided by QuikSCAT or by the Advanced Scatterometer on the European Organisation for the Exploitation of Meteorological Satellites's (EUMETSAT's) MetOp-A spacecraft. In order to simulate the performance of XOVWM and QuikSCAT for hurricanes, it is essential to be able to simulate realistically both wind and rain. For the simulation of these wind fields, we used the state-of-the-art Weather Research and Forecasting (WRF) Model (http://www.wrf-model.org) and drove the model with boundary conditions provided by NOAA. These lower resolution fields were provided by NOAA using NOAA Geophysical Fluid Dynamics Laboratory (GFDL) model runs for test cases selected by NOAA. The simulation fields were given to NOAA to validate the physical reasonableness of the simulations, and were then used as a basis for simulating the instrument response at Ku- and C-band and these simulated data were processed with the wind estimation algorithms developed under this task (further details are given in [3]). NOAA and JPL selected the following cases for simulation and evaluation:

- **Hurricane Katrina**: a well-studied hurricane with high winds in the coastal zone. Winds to category 3, heavy rain, and a large eye.
- **Hurricane Rita:** an intense hurricane with a smaller spatial extent to test spatial resolution performance.
- **Hurricane Helene:** a hurricane that could be tracked as it evolved from a tropical to an extra-tropical cyclone.

Figure 4 shows hurricane wind speed performance that is typical of QuikSCAT and XOVWM. QuikSCAT shows good skill up to wind speeds of ~40 kts, but greatly underestimates the wind speed above ~40 kts. XOVWM, on the other hand, shows good skill for all wind speeds, with little degradation in the retrieval even for high winds.

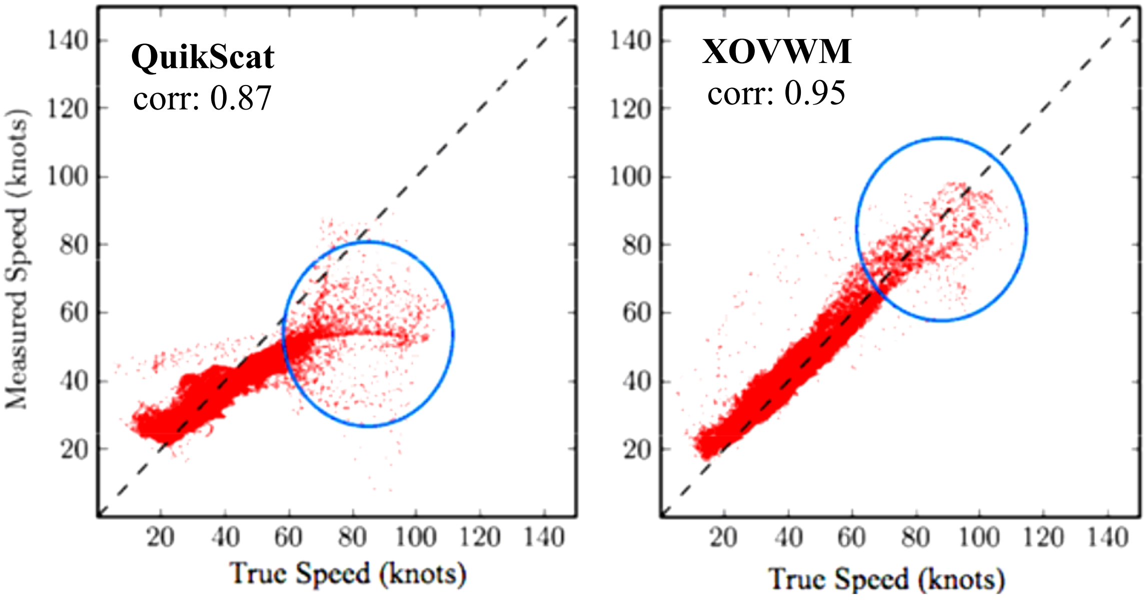

Figure 4: *Wind speed retrieval performance for Hurricane Rita using the XOVWM instrument (right) and a QuikSCAT Replacement instrument (left). The lower axis represents the "true" wind speed from the WRF hurricane simulation, while the y-axis represents the measured wind speed. The blue circle highlights the wind speed performance at high wind speeds (category 1 hurricanes start at 64 kts). Note that while a QuikSCAT-type instrument significantly underpredicts wind speeds for hurricane-level winds, the XOVWM instrument is able to measure wind speed accurately for the entire range of wind speeds.*

Figure 5 shows the results of the WRF simulation runs for Hurricane Katrina, which will be used to compare QuikSCAT Replacement and XOVWM performance below. Notice the very heavy rain present near the hurricane eye-wall and winds reaching into category 3 on the Saffir-Simpson scale.

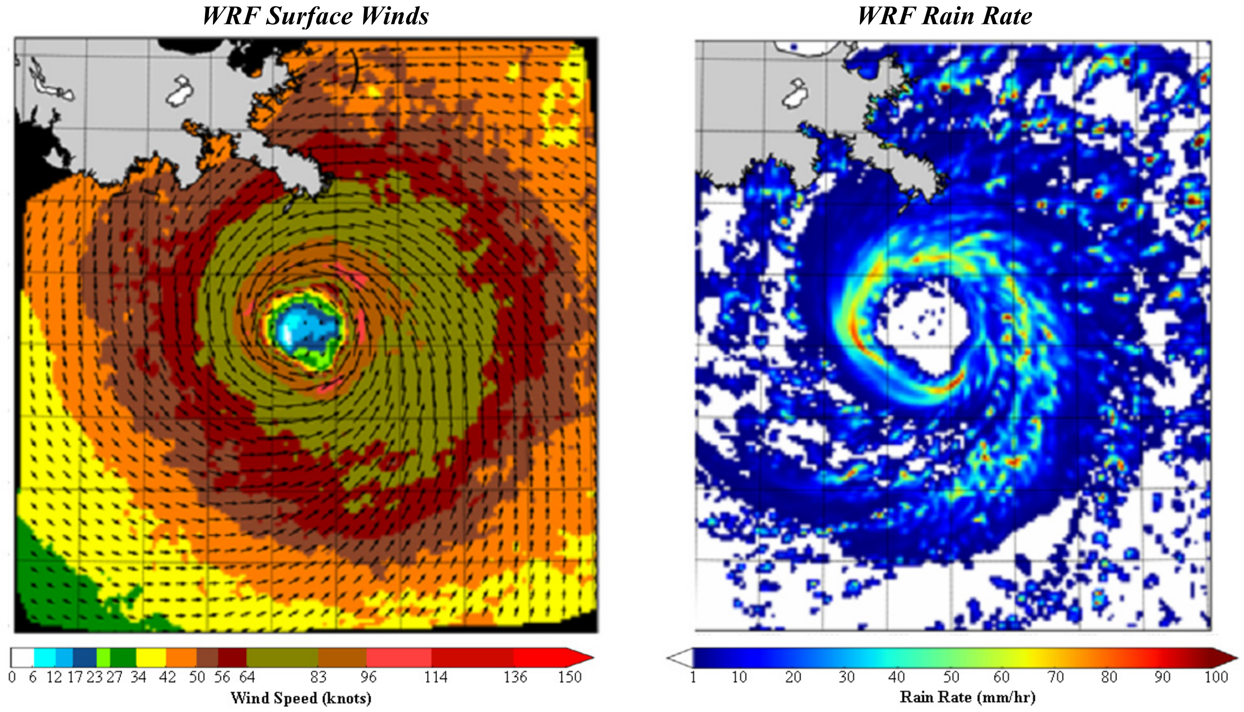

Figure 5: *WRF "truth" wind field (left) and rain rate for Hurricane Katrina as it approached land near New Orleans. The wind speed is color coded so that wind speeds above 64 kts represent different category hurricanes. NOAA is required to report the 34-kt, 50-kt, and 64-kt wind speed radii. The figure on the right shows the rain field. Rain rates above ~30 mm/hr (~1.2 in/hr) (light blue and above) will significantly degrade the performance of a QuikSCAT-class scatterometer.*

Figure 6 shows the performance of each system relative to NOAA's wind speed radii requirements[1] by depicting retrieved winds from simulated QuikSCAT and XOVWM instrument observations for the fields shown in Figure 5. The QuikSCAT results exhibit many of the peculiarities of true QuikSCAT data, including the mislocation of the hurricane center and significant underestimation of the winds. XOVWM retrievals, on the other hand, agree well with the true winds both in magnitude and structure. A user from the TPC/NHC noted in the user impact study [3] that these data "convincingly show that XOVWM provides more accurate retrievals than QuikSCAT in most portions of the WRF-simulated circulation."

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[1] The wind speed radii evaluation was provided to JPL by Zorana Jelenak and her colleagues at NOAA.

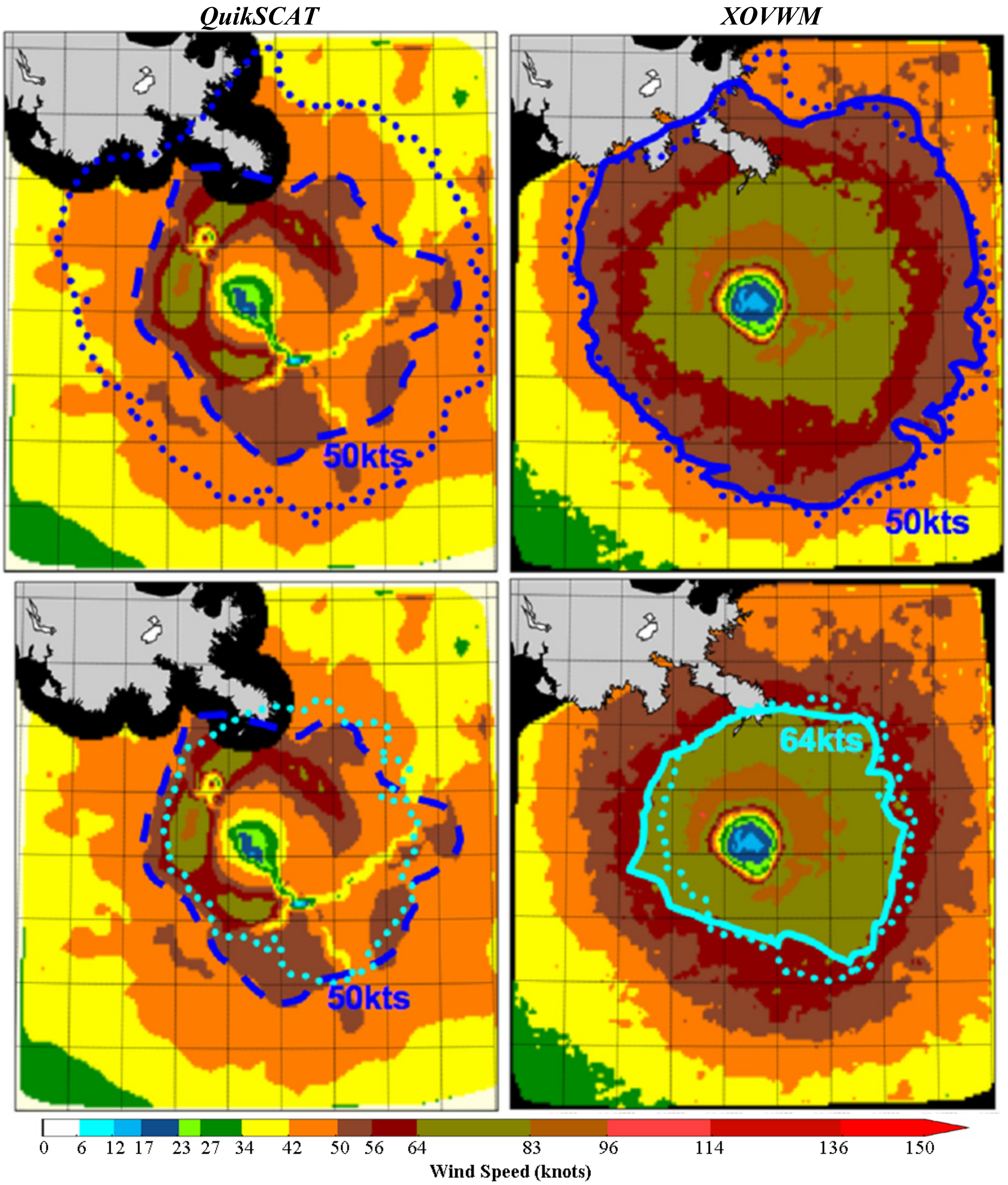


Figure 6: *Estimated wind speeds for the Hurricane Katrina example shown in Figure 5 for XOVWM (right) and the QuikSCAT Replacement (left). The QuikSCAT Replacement performance shows many of the artifacts observed by NOAA for real QuikSCAT data over hurricanes. The hurricane center is displaced relative to the true center and the wind speeds are severely underestimated. NOAA is required to report on 34-kt, 50-kt, and 64-kt wind speed radii. As part of the NOAA user evaluation process [3], NOAA has estimated the wind speed radii for this example. The 34-kt radii (not shown) are accurately predicted by both instruments. The XOVWM wind radii (solid lines) reflect the true wind radii (dotted lines) for both the 50-kt (upper right) and 64-kt (lower right) wind radii. QuikSCAT (dashed lines), on the other hand, is not able to reproduce either of these wind radii accurately. The upper left image shows that the 50 kt wind speed radii are significantly underpredicted by QuikSCAT. The lower left image shows that no 64 kt radii could be obtained from QuikSCAT, although, coincidentally, the estimated 50 kt wind radii coincided with the true 64 kt radii. Notice, furthermore, that due to QuikSCAT's inability to measure winds near the shoreline, storm- and hurricane-level winds, which exist in the coastal region, can only be measured by XOVWM.*

A detailed interpretation of the impact of XOVWM measurements by the NHC can be found in the NOAA user impact study [3]. Among the conclusions of this study are the following:

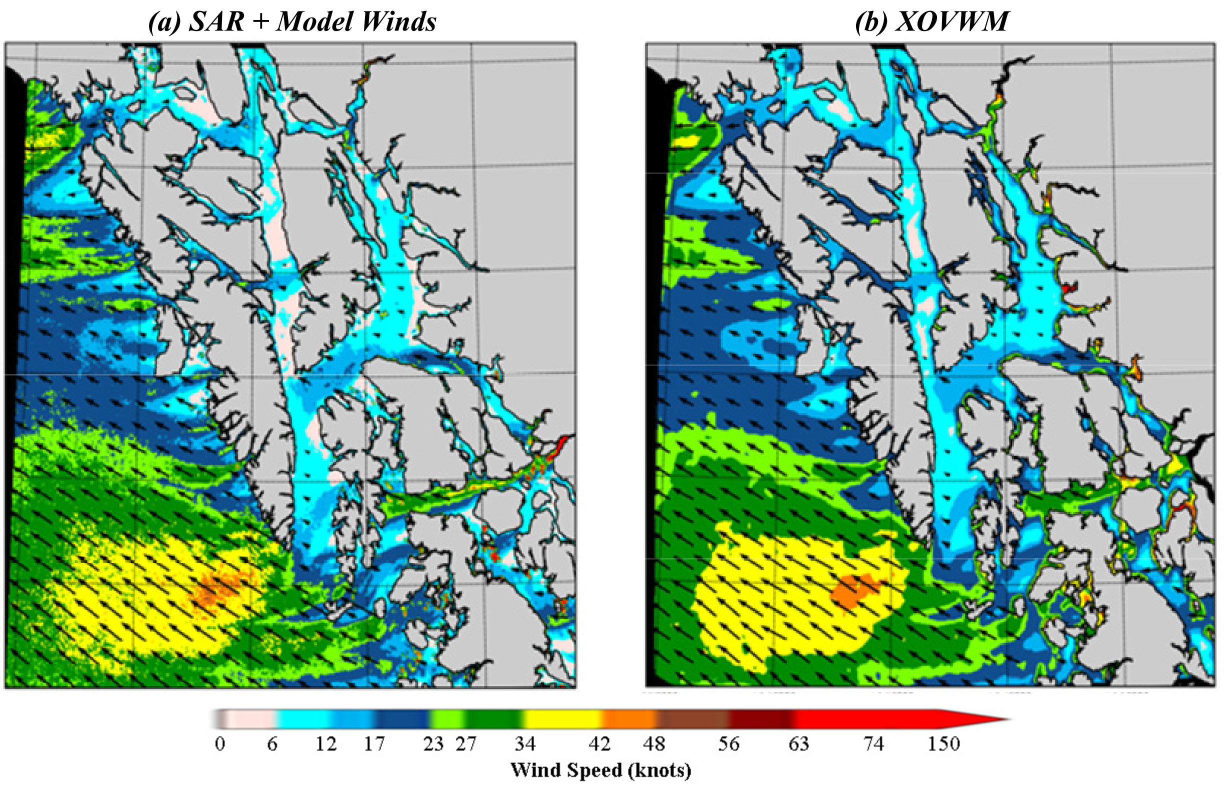
> "… there is just no comparison between XOVWM and QuikSCAT. The XOVWM simulations are clearly superior to QuikSCAT for estimating hurricane intensity. Improved intensity estimates from XOVWM would not only improve hurricane analysis in NHC's areas of responsibility, but also in other tropical cyclone basins of the world where aircraft reconnaissance is rarely, if ever, available. Improved monitoring of hurricane intensity worldwide, especially if a XOVWM or similar capability would be adopted long-term, would serve well the efforts of the climate community to assess relationships between hurricanes and climate change.
>
> "QuikSCAT wind direction retrievals do not even come close to accurately depicting where the center of the hurricane is located, while XOVWM directions do accurately depict the center. Second, QuikSCAT retrievals are not produced as close to the coast … as with XOVWM, which limits its utility in both estimating the extent of hurricane-force winds (wind radii) and in providing data for local NWS forecast offices. Given this comparison, an operational forecaster could place much more confidence in XOVWM when it passes over a hurricane.
>
> "A capability such as this to obtain a reasonably accurate two-dimensional wind field of even a major hurricane would represent a very significant enhancement to NHC operations. The benefits would be especially noticeable when aircraft reconnaissance data are not available (which is the case much of the time in the Atlantic and nearly all of the time in the rest of the world).
>
> "Nevertheless, it is our assessment, based largely on the JPL study results, that even a single XOVWM satellite would represent a major step toward meeting critical aspects of our operational OSVW requirements (such as retrievable wind speed range to include major hurricanes), which is not provided by the current QuikSCAT and would not be provided by a QuikSCAT duplicate."

1.2.2 Coastal Winds

Aside from high winds and rain, the other major performance capability that distinguishes QuikSCAT from XOVWM is its ability to map wind fields at high resolution and near the coasts. Although high-resolution winds near the coast are not routinely available, synthetic aperture radar (SAR) instruments, such as the Canadian RADARSAT, have the capability of providing high-resolution (500-m) wind speed (not direction, in general) estimates. These wind speed estimates can be complemented with model direction results to obtain estimates of winds near the coasts that are felt by NOAA to be representative of the phenomena of interest in the coastal region.

Based on NOAA user inputs for the 2006 NOAA Ocean Winds Workshop Report [2], and on the availability of appropriate SAR data, NOAA and JPL jointly selected a number of coastal scenes which could demonstrate to NOAA the impact of XOVWM high resolution data. The data sets selected covered the Alaska and California coasts, where high localized winds are common and are known hazards to shipping and fishing. An additional advantage of selecting these regions is that the NOAA users were already very familiar with SAR data and the implications of high-resolution data availability.

Figure 7 shows a comparison of QuikSCAT and XOVWM performance along the Alaska coast near Juneau and Sitka. Similar examples of these performance differences can be found in the user impact study [3]. As can be seen from this figure, the XOVWM instrument captures all of the important features critical to the coastal regions, while QuikSCAT misses many of them.


(a) SAR + Model Winds

(b) XOVWM

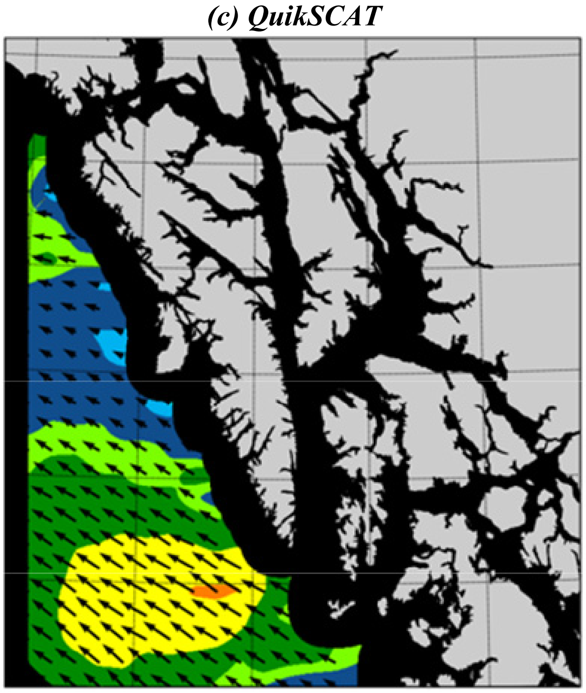

(c) QuikSCAT

Figure 7: *(a) High-resolution winds derived from SAR and model data for the Alaska coast, including Juneau and Sitka. Notice the gale-force wind jets in the coasts and in the inner channel. (b) XOVWM measurements of these winds accurately retrieve the wind jets and their intensity. (c) QuikSCAT, on the other hand, misses most of the jets and cannot cover the coast or the inner passage due to its land mask. The area of storm level winds is also underestimated. There is heavy shipping activity in the areas missed by the QuikSCAT coverage.*

A detailed interpretation of the impact of XOVWM measurements on coastal winds monitoring can be found in the NOAA user impact study [3]. Among the conclusions of this study are the following:

> **Alaska Region Weather Forecast Office (WFO):** “It is important to recognize that improvements to the marine forecast and warnings have been accomplished using 25 km ocean vector winds. The NWS [National Weather Service] Alaska Region has a requirement for much higher resolution winds, especially in the complex coastal waters. For instance in Southeast Alaska, much of the marine activity occurs in the

inland waters where the vessels use the 'Inland Passage.' Although these waters appear at first to be protected, the islands contain high mountains, and there are major tidal current swings that can cause wind waves to stack higher. The 25 km QuikSCAT winds offer at most one data point along these inland passages. 5 km resolution ocean vector winds would provide sufficient information to assist the forecaster in making accurate and timely forecasts for these waters. In addition, 5 km resolution ocean vector winds would provide critical information much closer to the shore for Alaska's entire coastline. The higher resolution winds would provide a more detailed look at the winds associated with marine storms that can reach hurricane force in Alaska. With newer technology, the forecaster would also obtain a full wind speed range that now cuts off at higher speeds with 25 km data. The high ocean vector winds would provide vital information between the few buoys that surround Alaska.

"Last but not least, higher resolution QuikSCAT data will greatly improve the sea ice information. The commercial fisheries prefer to set their nets and traps right at the sea ice edge. There is increased cruise ship traffic in the Arctic as sea ice free areas grow and the season lengthens. There is anticipated growth in marine transportation in the next few years. It is nearly impossible to put weather buoys in the Arctic where sea ice can destroy them. There will be nearly complete reliance on satellite derived ocean vector winds and sea ice information.

"The NWS Alaska Region fully supports the need for a higher resolution ocean vector winds. The benefits of this data have much greater implications than just for the Alaska Region. All NWS Regions with coastal responsibility will benefit from this information."

Southern Region WFO: "Far and away, the most frequent perceived benefit of the advanced XOVWM scatterometer would be the potential availability of surface vector wind data much closer to the coast. The current QuikSCAT masking of data within 30 km of the coast is precisely where most recreational boating occurs and where most marine deaths occur due to strong winds and associated large waves. Coastal topography plays a huge role in these events, and local effects are either not observed by QuikSCAT or are observed only peripherally."

Western WFO: "The most frequent perceived benefit of an advanced scatterometer capability cited by WR coastal offices regards the potential availability of surface vector wind data much closer to the coast (compared to current QuikSCAT). Most west coast marine user activity occurs within a few miles of the coast – well inside the current QuikSCAT coastal masking area. Strong wind events are common on the west coast in both winter (occasionally exceeding hurricane force) and summer (commonly up to gale force), yet the current QuikSCAT data masking prevents observation of winds close to the coast, where most marine user activity occurs. This is also the area where most marine deaths occur, due to strong winds and associated large/steep waves. All WR coastal offices have noted the occurrence of significant coastal wind events close to shore at various times of the year, and often influenced by coastal topography, e.g. coastal barrier jets, land-falling fronts, and eddies, which are either not observed, or only peripherally observed by the current QuikSCAT. In most areas, the existing coastal observation network (e.g. buoys and C-MANs) are also insufficient to consistently and reliably resolve these wind features."

Central Pacific Hurricane Center and Pacific Region: "Pacific Region local office marine forecast responsibilities includes channels between the Islands. Due to the extreme topography variations surrounding these channels, synoptic winds are often accelerated creating hazardous conditions. Scatterometer data are used to make marine warning decisions. Increasing commerce and recreational activities in these channels, such as ferries used to transport people and supplies, make accurate and detailed forecasts in these waters a critical requirement for our users; however the current land masking effects make scatterometer observations impossible in most channels. Therefore, a reduced land mask effect is required to enable valuable scatterometer observations to be made and used in these busy waterways."

1.2.3 Extra-tropical Cyclones

Extra-tropical cyclones are a significant hazard to shipping. One of the great successes of the use of QuikSCAT data at NOAA has been the ability to provide operational forecasts and warnings of hurricane-level winds for extra-tropical cyclones [5], a capability that did not exist prior to QuikSCAT.

To evaluate the XOVWM capability, Hurricane Helene was simulated as it transitioned from a tropical to an extra-tropical cyclone. These data, along with the other simulation data, were evaluated by the NOAA Ocean Prediction Center. Their recommendation is given below:

> "The loss of QuikSCAT capabilities will be devastating to the OPC, especially for detecting and warning for extratropical cyclones with the most dangerous and severe conditions, those that reach hurricane force intensity. There are limitations to the QuikSCAT capability. Those limitations do hinder the day to day service. The JPL results for XOVWM would greatly address many of those limitations especially the all weather capability and high wind retrievals. It is significant that the XOVWM would be able to extend coverage nearly to the coastlines. These improved capabilities would allow OPC to detect and warn for extreme wind conditions in extratropical cyclones, to improve warnings for areas of rain such as convection, small moist extratropical cyclones, and north of warm frontal boundaries. The coastal capability would enhance coastal WFO's detection capabilities for a variety of phenomena including gap winds, coastal jets, and offshore convection. OPC has benefited greatly from satellite remotely sensed OSVW, offices with mainly coastal responsibility much less so. An XOVWM would greatly benefit all NWS offices with marine responsibility and would bring OSVW capability to the realm of many many marine users. Therefore from the view point of service value and this improved technical capability, *XOVWM is by far the preferred solution*[2]. A single satellite solution would give increased capabilities but temporal sampling would continue to be a problem for lower latitudes and for rapidly developing cyclones. It is requested that a two satellite solution be given very serious consideration to address these needs." [3]

1.2.4 Summary of Impact to NOAA

In addition to collecting inputs from the NOAA users, the NOAA user impact study [3] provides an assessment of the need for wind measurements, and a comparison of the capabilities of the QuikSCAT follow-on options studied in this report with other options available to NOAA to meet its operational Ocean Surface Vector Winds (OSVW) requirements. The primary conclusion of this report is that OSVW data are required by all NOAA Goal Teams and have been identified as critical data needed for the Local Weather and Forecasting and Commerce and Transportation Team's weather forecast and warning products. These data have been assigned CORL Priority 1 for many applications, meaning not having these data will prevent performance of the mission or preclude satisfactory mission accomplishment.

The suitability of the options presented here, as well as other existing OSVW data sources, as assessed by NOAA users is presented in Table 3. From this table, it is clear that to maintain the significant improvements in operational weather forecasting and warning applications that have resulted from the availability of QuikSCAT OSVW data, continuity of the OSVW data stream at a level that is equivalent to or better than that provided by QuikSCAT is required. All NWS users have set the QuikSCAT-equivalent capability as a minimum for threshold OSVW capability. It is also clear from Table 3 that the XOVWM mission would greatly enhance the detection and warning capability across a wide range of weather phenomena for nearly all of the coastal, offshore, high seas, and Great Lakes areas of responsibilities, and that for most applications the XOVWM options have a high impact on NOAA applications, while the other available options generally have medium and low impacts. From all inputs received from NWS forecast offices and centers, the most significant conclusion is that even a single XOVWM would be a major step toward meeting critical aspects of OSVW operational requirements compared to a QuikSCAT-equivalent solution.

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[2] Emphasis in the original.

Table 3: *Impact of the QuikSCAT Follow-On Mission options (QuikSCAT and XOVWM options) and other existing OSVW data sources (ASCAT and WindSat) on NOAA Ocean Surface Vector Winds applications.* ***Low impact*** *(L, red) – performance below threshold needed for satisfactory application product support.* ***Medium impact*** *(M, yellow) – performance between threshold and objective requirements needed for full application product support.* ***High impact*** *(H, green) – performance close or at objective requirements necessary full application product support [3].*

Application		QuikSCAT	ASCAT	WindSat	XOWVM
Marine Weather	**High Seas**	**M**	**L-M**	**L**	**H**
	Off shore	**M**	**L-M**	**L**	**H**
	Coastal wind	**L**	**L**	**L**	**M-H**
	Coastal swell	**L-M**	**L-M**	**L**	**H**
Tropical Cyclones	**Intensity**	**L-M**	**L**	**L**	**H**
	Genesis	**M**	**L-M**	**L**	**H**
	Location	**M**	**L-M**	**L**	**H**
Real-Time Diagnostics	**Wind**	**M**	**L-M**	**L**	**H**
	Swell	**M**	**L-M**	**L**	**H**
	Extratropical storm surge	**M**	**L-M**	**L**	**H**
	Inland Impact	**L**	**L**	**L**	**H**
Climatology	**Extratropical cyclone**	**H**	**L-M**	**L**	**H**
	Wind	**H**	**M**	**M**	**H**

Section 2: Overview of Mission Options Studied

> *Preliminary mission concepts have been developed for three QuikSCAT follow-on options for transitioning ocean surface vector winds measurements to a National Oceanic and Atmospheric Administration (NOAA) operational system. The three options are 1) a functional replacement for QuikSCAT, 2) the Extended Ocean Vector Winds Mission (XOVWM) system described in Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond from the National Research Council (NRC), and 3) a constellation of two XOVWM spacecraft.*

Three mission options were considered in this study: a QuikSCAT Replacement, XOVWM, and an XOVWM Constellation. For the QuikSCAT Replacement option, an instrument that is functionally equivalent to the SeaWinds/QuikSCAT instrument was designed which, by definition, meets the current performance of QuikSCAT but does not meet the desire for improved high resolution and all-weather capabilities. The XOVWM instrument design, on the other hand, provides high resolution and all-wind/weather capabilities via incorporation of a larger antenna, an additional scatterometer channel at C-band, and a passive radiometer channel at X-band. By tailoring the spacecraft power system appropriately, the XOVWM instrument and spacecraft can be designed to enable operation in any sun-synchronous orbit; hence, the same fundamental design is used for both the XOVWM single spacecraft and constellation options. Table 4 provides a high level comparison of the QuikSCAT Replacement and XOVWM payload characteristics. Further details are provided for each option in subsequent sections.

Table 4: *High-level comparison of key XOVWM and QuikSCAT Replacement payload characteristics*

Parameter	QuikSCAT Replacement	XOVWM
Scatterometer	Ku-band	Ku-band, C-band
Radiometer	*none*	X-band
Antenna size	1 meter	3.5 m by 5 m
CBE Mass	155 kg	320 kg
CBE Power	190 W	790 W
CBE Uncompensated momentum	40 Nms	300 Nms
Uncompensated momentum + margin	55 Nms	400 Nms
Ku-band spatial resolution	25 km x 6 km	<5 km x 1 km
C-band spatial resolution	*N/A*	<20 km x 1 km
X-band spatial resolution	*N/A*	<10 km x 10 km
Spin rate	18 rpm	20 rpm
Data rate	30 kbps	1 Mbps

NOTE: CBE = current best estimate

Section 3: Implementation with a QuikSCAT Replacement

A QuikSCAT Replacement instrument, functionally equivalent to the SeaWinds/QuikSCAT instrument, has been designed. This instrument, by definition, meets the current performance of QuikSCAT but does not meet the desire for high resolution and all-weather capability discussed in Section 1.

The QuikSCAT Replacement instrument is designed to be functionally identical to QuikSCAT, including performance parameters and downlinked data stream. However, the actual implementation differs for two reasons. First, much of the technology used for QuikSCAT is simply no longer available; hence, it is not possible to manufacture a new instrument based on the schematics and drawings. Second, the philosophy behind the QuikSCAT Replacement option is to develop an instrument that can be easily evolved to have enhanced capabilities in subsequent generations. In the original QuikSCAT design, the instrument is fixed; only the antenna rotates. Microwave power is sent to and from the antenna using a rotary joint. This works well for a single frequency system with only two beams. However, rotary joints for spaceborne operation are currently limited to only two or three channels. This makes it virtually impossible to add an additional scatterometer frequency and a radiometer channel to the original QuikSCAT architecture. For this reason we have taken a different architectural approach for the QuikSCAT Replacement option (Figure 8) in which the entire instrument is spun, similar to many spaceborne radiometers (e.g., WindSat), in order to provide a path for a relatively straightforward transition between QuikSCAT Replacement and Extended Ocean Vector Winds Mission (XOVWM) capability. The XOVWM design (described in the next section) also uses this approach.

Figure 8: *A QuikSCAT Replacement spacecraft*

Figure 9 shows the original QuikSCAT data acquisition geometry. The same geometry is used for QuikSCAT Replacement. The QuikSCAT Replacement antenna is a 1-m solid dish (see Figure 10), essentially identical to that of QuikSCAT. It has two Ku-band feeds, one providing a 40-degree look angle for the inner beam and the other providing a 46-degree look angle for the outer beam. The antenna is connected directly to the high-power transmit amplifier (a Traveling Wave Tube Amplifier [TWTA]) and receiver via waveguide and a switching network. No rotary joint is needed, since the entire instrument spins at 18 rpm. The switching network also provides for routing the transmitted pulse directly into the receiver for calibration. The design of the radio frequency (RF) electronics is similar to QuikSCAT. A pulse is generated, upconverted to Ku-band, and then transmitted through the inner or outer beam; the beam alternates on a pulse-by-pulse basis. The TWTA would be an improved version (smaller and lower mass) of the TWTA used for QuikSCAT. The receiver would have better noise performance, due to improved technology, but would otherwise be similar to QuikSCAT. The digital subsystem would be implemented with field programmable gate arrays (FPGAs), in contrast to the microprocessor-based digital subsystem for QuikSCAT. An FPGA would be used to implement the onboard processor, instead of the FFT chip used in QuikSCAT. Since the entire instrument spins, signals and power are transferred to and from the spacecraft via a spin mechanism and slip ring assembly. As shown in Table 4, the QuikSCAT Replacement payload is expected to consume about 191 W, a portion of which must be radiated to maintain thermal balance. Thermal radiators surround the instrument, with a radiator surface area on the order of 1 m^2. The instrument concept is shown in Figure 10. A high-level functional block diagram showing the main subsystems for the instrument is presented in Figure 11.

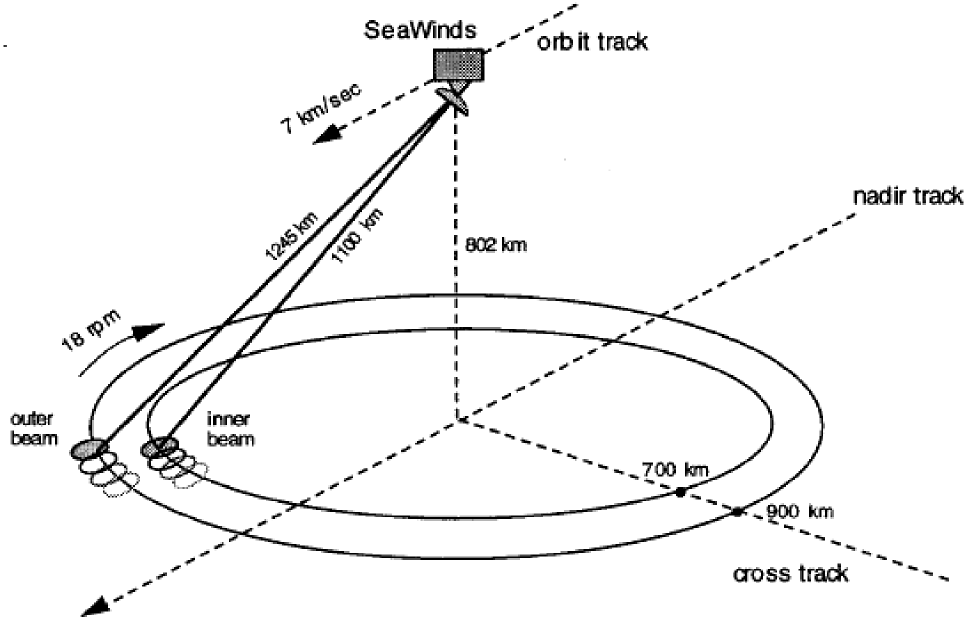


Figure 9: *Basic pencil-beam scatterometer geometry used to build an 1800-km swath. Two beams using slightly different incidence angles are scanned circularly about the nadir direction. Every point in the swath is visited from several different directions, allowing the retrieval of both wind speed and direction.*

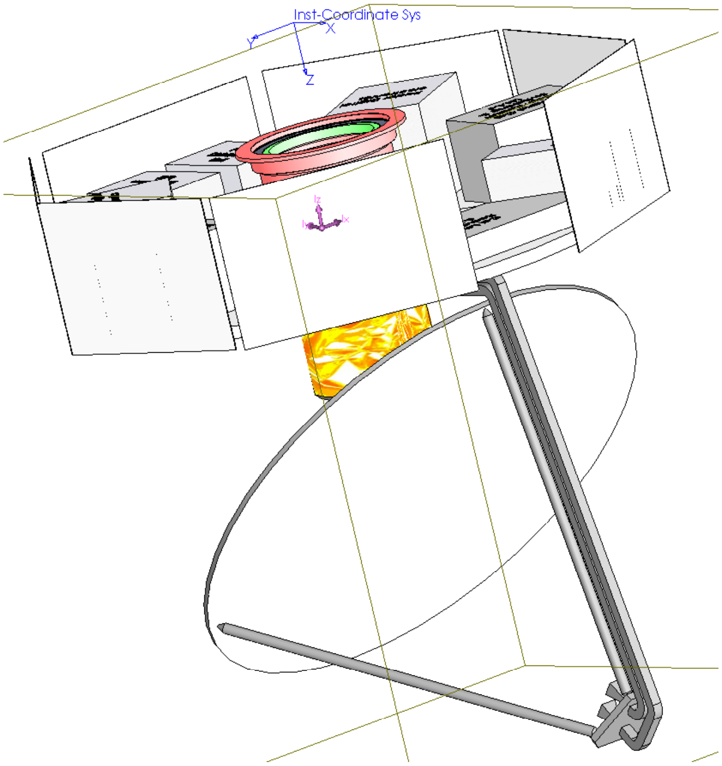


Figure 10: *QuikSCAT replacement instrument configuration with 1-m antenna. Panels surrounding instrument are thermal radiators.*

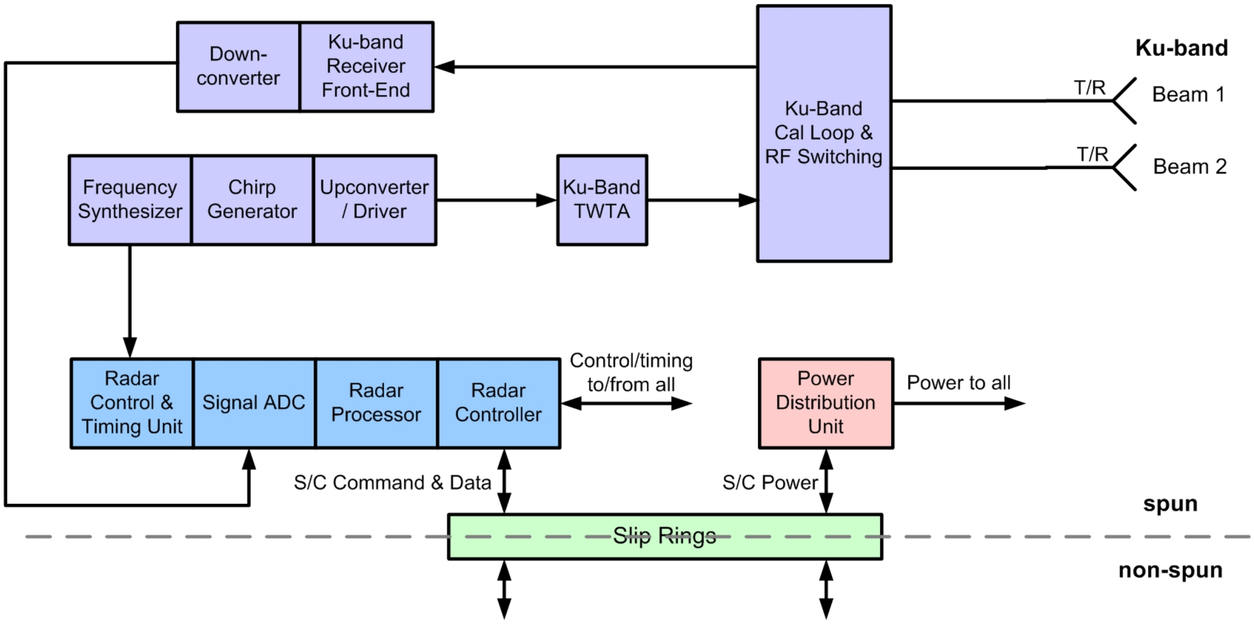


Figure 11: High-level functional block diagram of the QuikSCAT Replacement scatterometer

Section 4: Implementation of Needed Capability with XOVWM

In response to the community's requirements for improved operational ocean vector winds measurement capability, an instrument architecture has been developed for Extended Ocean Vector Winds Mission (XOVWM) leveraging complementary sensors and heritage technologies.

4.1 XOVWM Instrument Capabilities

XOVWM design uses a pencil-beam approach demonstrated by QuikSCAT and also used in the QuikSCAT Replacement instrument design (Figure 9). However, XOVWM adds a C-band scatterometer channel and an X-band radiometer channel. It also adds a synthetic aperture radar (SAR) capability at Ku-band.

The three fundamental advantages that the new measurements provide are

1. All-wind capability from the addition of the C-band scatterometer;
2. All-weather capability and autonomous direction determination from the addition of the C-band scatterometer and the X-band radiometer;
3. Improved spatial resolution from the SAR processing of Ku-band.

These enhancements, described below, allow XOVWM to address the desired National Oceanic and Atmospheric Administration (NOAA) capabilities discussed in detail in Section 1. After describing the new measurements and their heritage, we then describe the XOVWM instrument itself.

4.1.1 All-Wind Capability

Scatterometry relies on a geophysical model function (GMF) that relates radar backscatter to wind speed and direction. The GMF relationship of backscatter and wind depends on radar parameters such as frequency, incidence angle, and polarization. Figure 12 shows the fundamental behavior of the GMF for Ku- and C-bands at HH and VV (i.e., same transmit and receive polarization) polarization, and several incidence angles (angle from the normal to the surface). Parts a and b of Figure 12 show that the backscatter at Ku-band stops increasing for wind speeds above about 40 m/s, while parts c and d show that the backscatter at C-band continues to increase. Thus, adding C-band provides significantly improved high wind speed performance. By combining Ku- and C-band, XOVWM achieves superior performance at all wind speeds, as shown in Figures 1, 3, 4, and 6.

4.1.2 All-Weather Capability

Experience with QuikSCAT has shown wind estimates derived exclusively from Ku-band observations are significantly degraded by rain. Rain has three effects that corrupt both the wind speed and direction determinations. Low rain rates attenuate the signal, while higher rain rates have enhanced backscatter from the rain drops. There is also a "splash" effect from the rain striking the surface. Scattering from rain is direction independent, and so in addition to corrupting the amplitude which mainly determines speed, the direction determination is also compromised. SeaWinds with Advanced Microwave Scanning Radiometer (AMSR) on the Advanced Earth Observing Satellite-II (ADEOS-II) allowed a detailed physical and empirical investigation of these effects. It is also known from the C-band scatterometers on ERS-1 and 2 and the recently launched European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) ASCAT that they are much less sensitive to rain.

Figure 13 shows that by adding C-band, the effects of attenuation and backscatter are greatly reduced so that scatterometer wind determination can be recovered in rainy regions. The XOVWM hurricane simulation results shown previously in Figure 1 also demonstrate this.

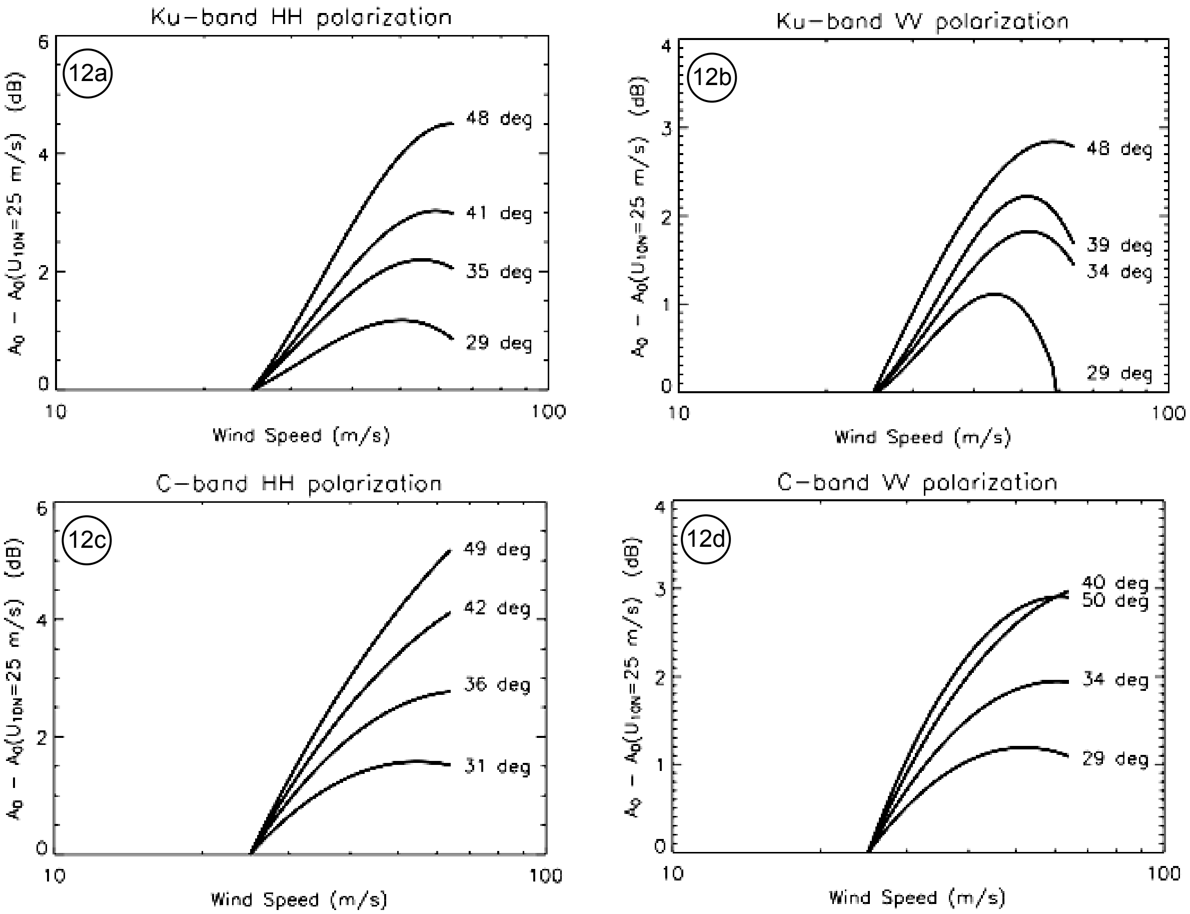


Figure 12: The "model function" represents the physical relation between radar backscatter (vertical axis) and true wind speed (horizontal axis). In order to be able to invert unambiguously, there should be only one wind speed for any given backscatter measurement. The measurements above show that, for Ku-band, the signal saturates and retrievals can only be performed for wind speeds below ~40 m/s (~80 kts) for horizontal (12a) or vertical (12b) polarizations. This physical limitation restricts the suitability of using a QuikSCAT-class scatterometer by itself for retrieving strong storm or hurricane level winds.

Although the results shown above indicate that a joint Ku- and C-band scatterometer can meet the NOAA requirements, performance risk for an operational mission could be reduced by adding a low-cost, polarimetric X-band radiometer system built on heritage from the Naval Research Laboratory (NRL) WindSat mission. The radiometer system would have two benefits to XOVWM:

1. Since X-band is very sensitive to rain, it would provide an independent method of improving the performance in rainy conditions. Figure 14 presents an example of the potential benefit of using a combination of active and passive channels for estimating and removing rain contamination. This example uses real data from the joint operations of the SeaWinds and AMSR instruments on the Japanese Aerospace Exploration Agency (JAXA) ADEOS-II platform in 2003.
2. The polarimetric information from the radiometer provides a wind direction signature that is complementary to that from the scatterometers. This differing response to wind direction can be used to autonomously remove ambiguities in the estimated wind directions without the use of Numerical Weather Prediction (NWP) model input—an advance over all space-borne ocean surface vector wind measuring systems to date. This not only makes the XOVWM winds fully independent of the models, but it also simplifies processing by not requiring the use of model input.

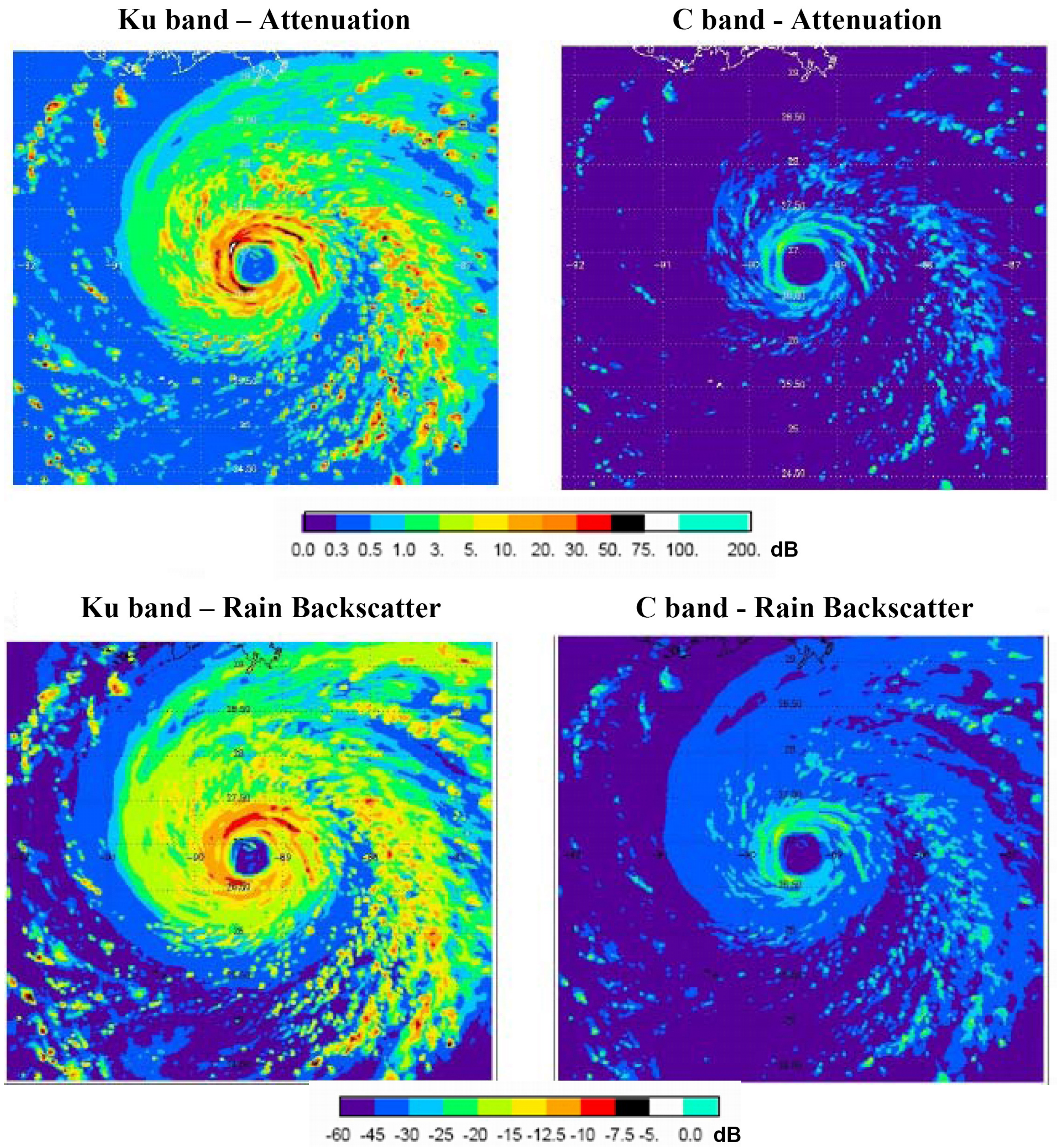


Figure 13: *Rain can distort the scatterometer signal by either attenuating the ocean signature (top row) or contributing a spurious back-scatter signature (bottom row). The scatterometer wind speed retrieval will be distorted significantly if either of these contributions is in the yellow to red zones, using the color tables above. This figure shows that Ku-band (left column) will suffer significant signal distortion in the regions of highest wind (i.e., near the eye wall), where heavy rain is prevalent. C-band (right column), on the other hand suffers significantly smaller distortions in heavy rain regions and lends itself to accurate wind retrievals in these regions.*

4.1.3 Improved Spatial Resolution—Ku-band Pencil-Beam SAR Scatterometer

One of the major enhancements of XOVWM over QuikSCAT is its improved spatial resolution (5 km for XOVWM vs. 12.5 km for QuikSCAT). Using its SAR and QuikSCAT heritage, the Jet Propulsion Laboratory (JPL) has shown in the refereed open literature [6] how a pencil-beam scatterometer must be modified in order to obtain the resolution desired by the NOAA users. The primary impact is that at Ku-band the antenna electrical aperture must be increased from 1 m to 3.5 m.

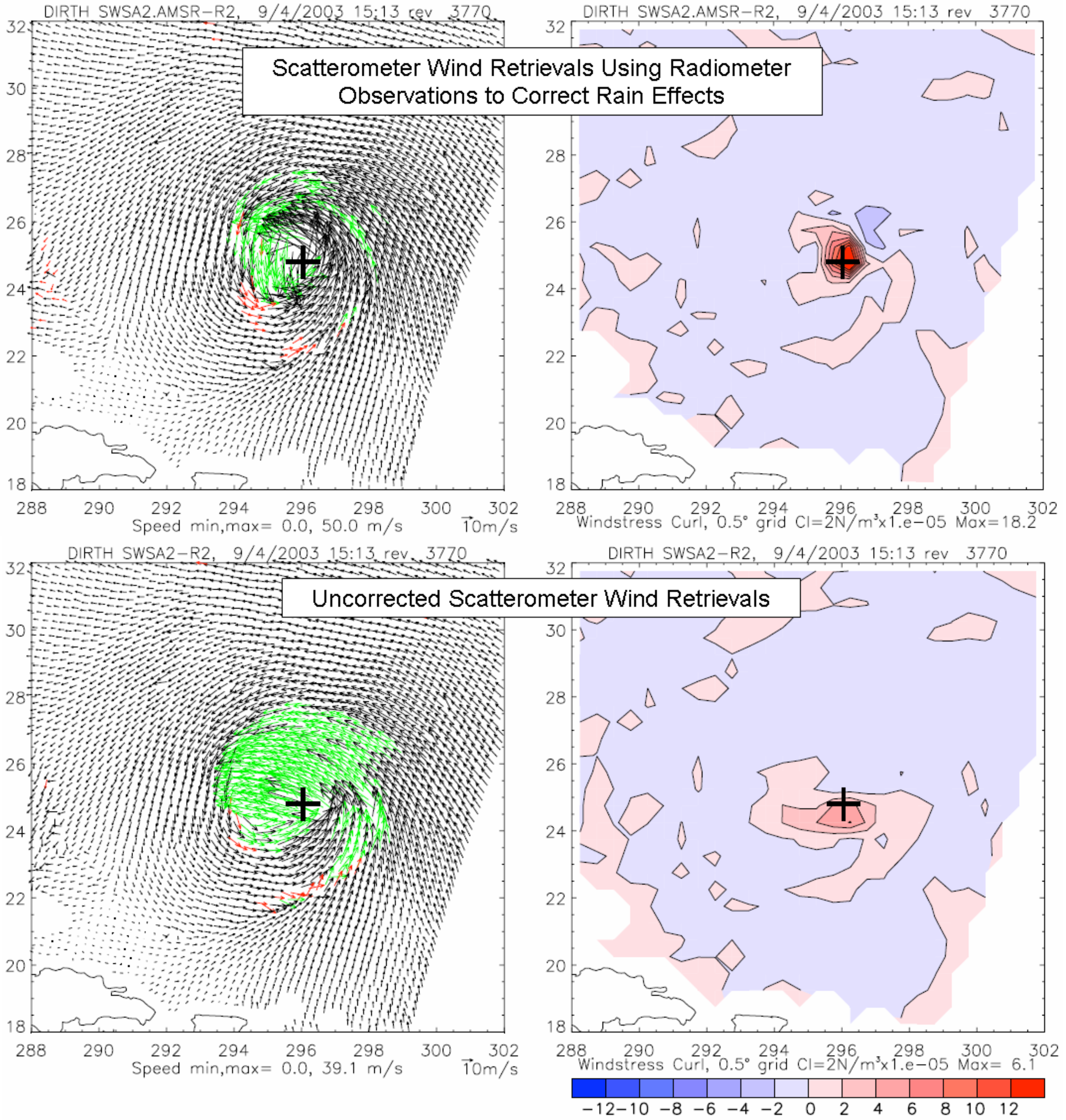


Figure 14: *Impact of using SeaWinds scatterometer data corrected with radiometer (AMSR) for wind retrievals in the presence of rain for Hurricane Fabian. The left column represents the retrieved winds, with rain-affected winds colored green. The top row shows the joint active/passive retrieval, while the bottom row shows the scatterometer-only retrieval. As can be seen, many fewer points are affected by rain after correction, and the hurricane circulation is much better defined by the joint retrieval. The right-hand column represents the wind stress curl, a key physical quantity that determines the amount of ocean mixing caused by the hurricane. The jointly retrieved values show a much more physical signature than the scatterometer-only retrievals.*

In addition to the increased antenna size, SAR needs onboard processing in order to reduce the much larger data volume that must be acquired to provide the improved resolution. This well-understood unfocused-SAR processing can be easily implemented in available electronic components to give an output instrument data rate of about 1 Mbps. Obtaining backscatter measurements at 5-km resolution allows wind retrieval in coastal areas (see Figure 7) and to define small scale features of storms and fronts (note the many small scale features in Figure 6).

4.2 XOVWM Instrument Heritage

Although the XOVWM instrument leverages the synergy between different measurements in a novel way, each of these measurements is individually well-understood and has spaceborne operational heritage. Figure 15 summarizes the heritage that has fed into the XOVWM instrument design.

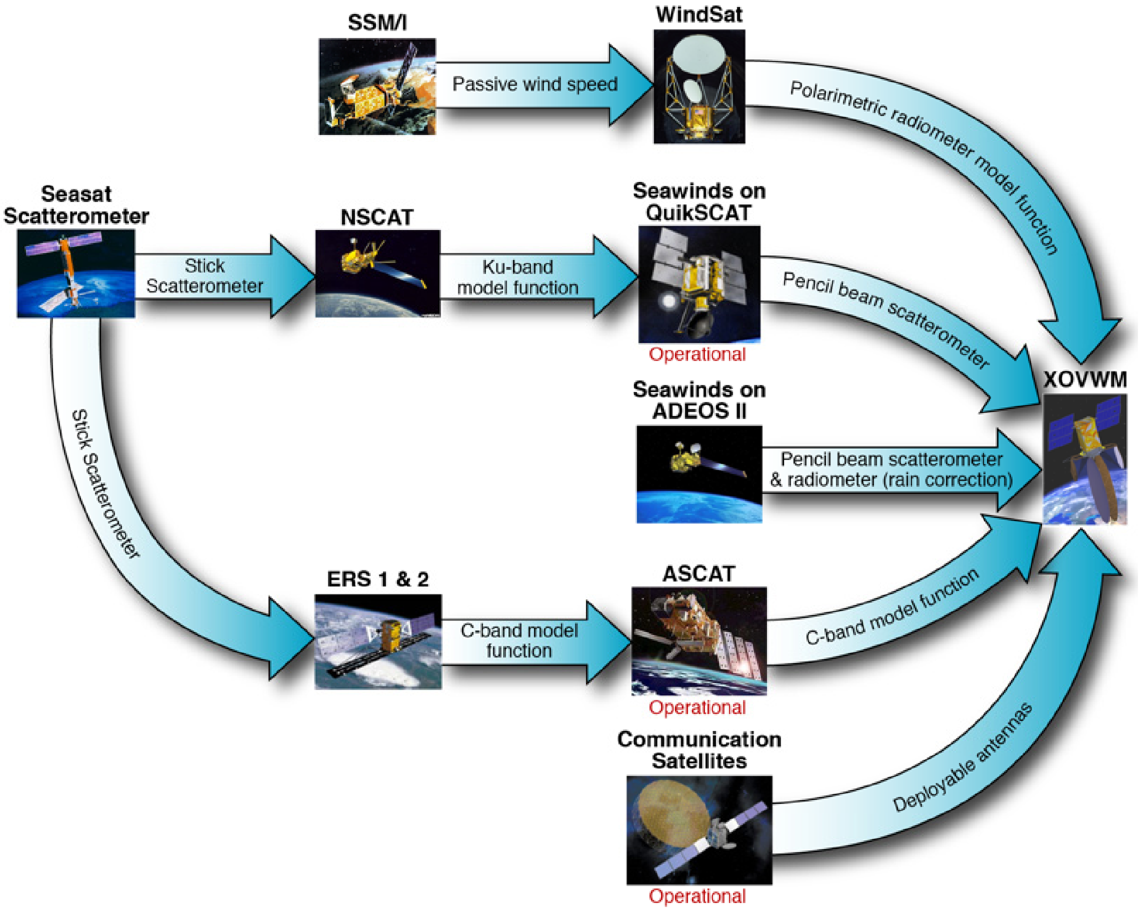


Figure 15: Measurement heritage leading to the XOVWM instrument

Ku-band Scatterometry: The first spaceborne Ku-band scatterometer was flown on the NASA SeaSat satellite, which launched in 1978 and introduced fan-beam design. A second-generation scatterometer (NSCAT) with similar fan-beam design but double the swath, was flown in 1996. Although the SeaSat and NSCAT scatterometers were successful, the fan beam design has a nadir gap in the coverage, which limits the usefulness of the data (a similar gap is present in the current EUMETSAT ASCAT scatterometer). An improved design, using a scanning pencil-beam antenna rather than multiple fan beams, was successfully demonstrated by the SeaWinds scatterometers on the NASA QuikSCAT satellite (1999–present) and the Japanese ADEOS-II platform (2003). This 30-year history of Ku-band scatterometry allows an excellent understanding of the capabilities and limitations of the Ku-band measurements. It has also allowed the accumulation of many years of experimental data verifying the instrument performance and developing the model function, which relates vector winds to the radar measurement.

C-band Scatterometry: In the early 1990s, the European Space Agency (ESA) launched a C-band scatterometer as part of the ERS-1 mission. A very similar scatterometer was launched as part of the ERS-2 mission. This line of scatterometer instruments culminated in the currently operating EUMETSAT ASCAT operational satellite, which launched in 2007 aboard MetOp-A. The two-decade investment in C-band scatterometry has led to an excellent understanding of the C-band model function and an assessment of the advantages and limitations of the C-band scatterometer winds. Additional data to extend and verify these data sets in hurricane and extra-tropical cyclone conditions have been collected by NOAA in airborne P3 campaigns.

Radiometer Winds and Active/Passive Combination: Radiometer wind speed (not direction) has been measured successfully for close to two decades by the SSM/I line of instruments. It is well known that the polarimetric signature is complementary to the scatterometer measurement and thus can be used to determine wind direction. NRL's experimental WindSat mission has demonstrated the capability of polarimetric radiometers to measure wind speed and direction. However, radiometer wind measurements have limitations in measuring the full range of wind speeds and operating in all-weather conditions. JPL demonstrated that significant wind performance improvements are possible in rainy conditions using a combination of active and passive measurements from the SeaWinds scatterometer and the AMSR radiometer on the ADEOS-II platform.

SAR Winds and Processing: Previous scatterometers have used real aperture radar technology, which limited their spatial resolution. High resolution winds from space have been demonstrated by the use of the Canadian RADARSAT SAR. This information is used operationally by the Alaska Weather Forecast Office (WFO). SAR processing is very mature, having been used for civilian spaceborne missions since SeaSat. Onboard spaceborne digital processing of scatterometer data for range compression has been demonstrated by the SeaWinds instruments. The added complexity of the processing required to generate the unfocused SAR images needed to achieve XOVWM's higher resolution is small and has been demonstrated multiple times by airborne platforms. The first spaceborne unfocused SAR radar instrument will be demonstrated in the soon-to-be-launched CryoSat-2 mission.

Deployable Antenna: The XOVWM design uses a 3.5 m by 5 m deployable mesh antenna to provide the aperture needed for Ku-band SAR and to improve the C-band real aperture resolution. These types of antennas, with apertures that can be significantly larger, have been manufactured and flown successfully by at least two-major U.S. contractors for over a decade. The main civilian application of these antennas has been the telecommunication industry, which has very stringent operational constraints. These antennas have also been used by the Department of Defense (DOD) and other security agencies, although the details are classified. The documented success rate for antenna deployment and performance has been very high. Further details of the XOVWM antenna are presented below.

4.3 XOVWM Instrument Characteristics

The main enhancements of XOVWM relative to QuikSCAT and QuikSCAT Replacement are:

- Larger antenna and SAR processing at Ku-band for high-resolution,
- C-band scatterometer channels, with the same viewing geometry as the Ku-band beams, and
- X-band radiometer channels with the same viewing geometry as Ku-band beams.

In designing the XOVWM scatterometer instrument for these new capabilities, many trade-offs were considered. The high-resolution capability of XOVWM requires a much larger aperture than the QuikSCAT; however, a larger antenna creates other issues (e.g., stowage volume and coverage). Based on these tradeoffs, the antenna aperture is increased from 1 m to 3.5 m (3.5 m x 5 m physical size). This change is required for SAR image formation and to achieve appropriate resolutions and signal levels at C- and X-bands. The finer resolution and antenna beam-width requires separate transmit and receive beams at Ku-band to avoid substantial loss due to the angular change in the antenna during the transmitted pulse roundtrip. Optimal beam spacing requires the feeds to be "overlapped" since fully separated feeds would generate beams with spacing that is too large.

The antenna is implemented as a lightweight deployable mesh antenna. The antenna is an offset-fed reflector with secondary flat reflectors to minimize deployment risk (see Figure 16). The reflector is illuminated on both sides and tilted slightly relative to the nadir direction to achieve the appropriate viewing geometry. (In practice, each Ku-band beam is implemented as two narrower sub-beams to optimize the instrument performance and coverage). Illuminating both sides of the reflector has the advantage of freeing up space to accommodate the feeds for all channels. It also allows feeds to be placed as close as possible to the reflector focal point; moving feeds away from the focus reduces gain and is undesirable. The resulting antenna design performs well electrically and is mechanically balanced, lessening the requirements levied on the spacecraft. The two C-band beams have the same viewing geometry and use the same reflector as the Ku-band beams. This is possible due to the large bandwidth electrical characteristics of the antenna mesh. These characteristics were verified experimentally at JPL as part of the present study.

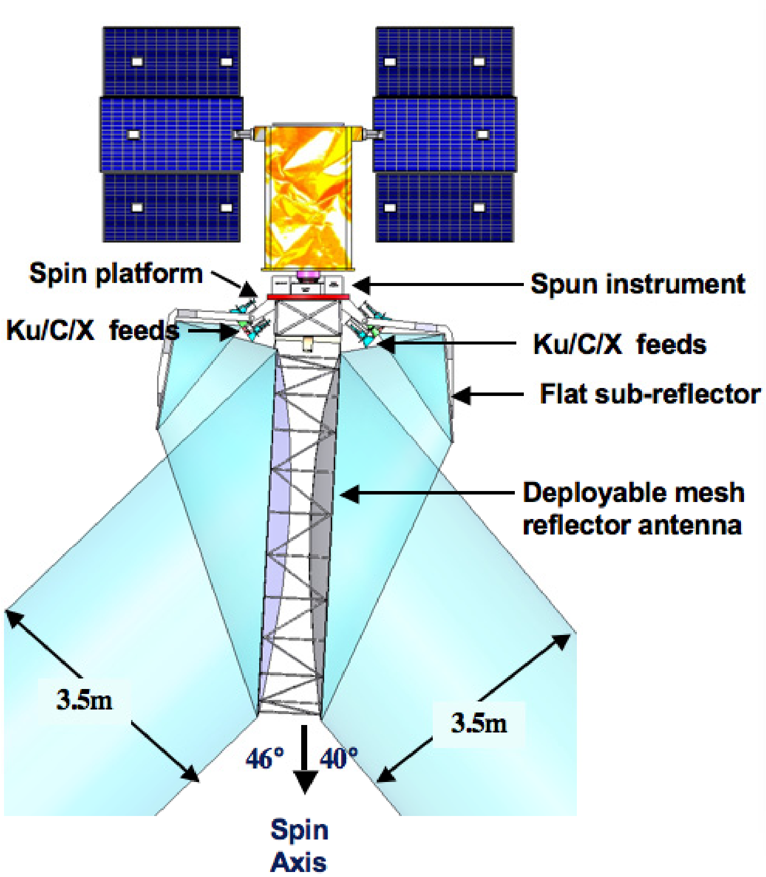


Figure 16: *Schematic of XOVWM showing key instrument components*

The onboard data processing would be enhanced relative to QuikSCAT and QuikSCAT Replacement by adding unfocused SAR. As part of this study, a software implementation of the onboard processing algorithm was completed to demonstrate the performance and reduce risk. The implementation of the onboard algorithm on a field programmable gate array (FPGA) chip was also studied and it was determined that the implementation was low-risk, feasible, and implementable with currently qualified flight parts. The onboard processor is part of the digital electronics subsystem, which also provides control and timing for the radar system. The radio frequency (RF) electronics is conceptually similar to that for QuikSCAT Replacement; it generates the transmit waveforms, and provides transmit and receive switching, calibration, signal reception, and down-conversion. However, it has more complexity due to the use of four Ku-band beams and two C-band beams. Since the instrument is spinning, communication with the spacecraft is via slip rings, as with the QuikSCAT Replacement instrument. Thermal control is provided by two radiators, with total area of 2.4 square meters. As shown in Table 4, XOVWM consumes more than twice the power of QuikSCAT Replacement, so the radiators are larger but present no serious problems. Figure 17 shows a high-level functional block diagram of the XOVWM instrument.

The X-band Polarimetric Radiometer (XPR) has only the reflector antenna in common with the radar; it has its own X-band feeds and receivers. The suitability of the mesh reflector electrical characteristics for radiometry was demonstrated experimentally as part of the study. The XPR utilizes proven flight designs from Jason-2/Advanced Microwave Radiometer, which are both multi-frequency single polarization radiometer systems. The XPR is a single frequency (10 GHz), direct detection, dual-polarization radiometer receiver in which all RF amplification and bandpass filtering is performed at 10 GHz. The RF chain is accomplished in a planar, microwave integrated circuit (MIC) architecture. The radiometer output is sent directly to the spacecraft solid-state recorders. Apart from the common reflector, the only connection between the Ku- and C-band radar and XPR is a blanking pulse from the radar that allows the radiometer to suspend integration during the radar transmit event. This avoids the possibility of interference with the radiometer.

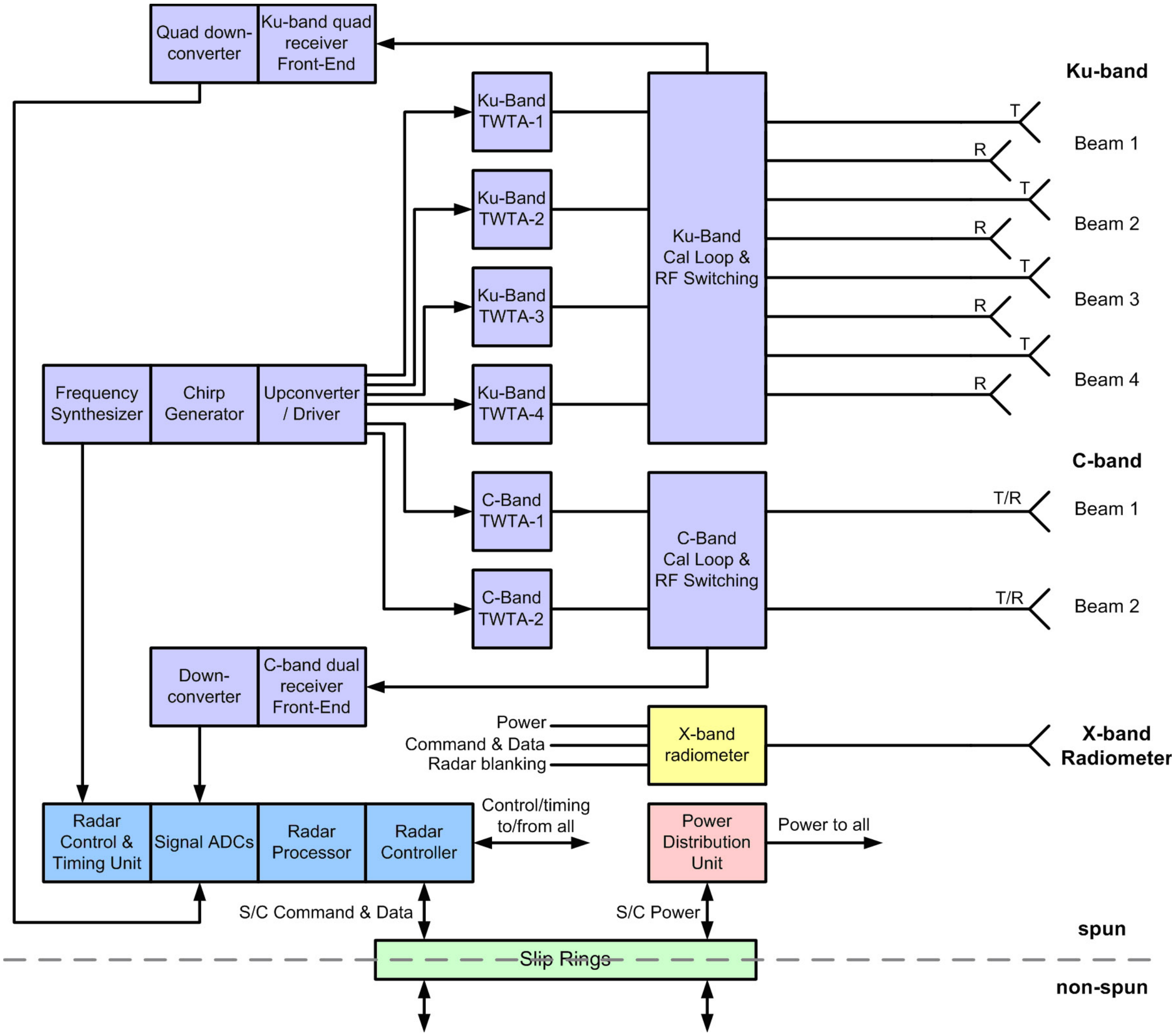


Figure 17: High-level functional block diagram of the XOVWM scatterometer

Section 5: Enhanced Capability with XOVWM Constellation

An Extended Ocean Vector Winds Mission (XOVWM) Constellation was considered as a cost-effective option to reduce revisit time between measurements. This option leverages the relative lower cost associated with building subsequent XOVWM spacecraft after completion of the initial non-recurring engineering associated with a first build. The XOVWM Constellation option consists of two identical XOVWM observatories, launched into two separate orbits to improve the revisit time between measurements.

The single satellite XOVWM option meets all of the National Oceanic and Atmospheric Administration (NOAA) measurement requirements (Table 2) with the exception of measuring 90% of the Earth's surface within 12 hours. Figure 18 shows that a single XOVWM satellite will cover 90% of the Earth's surface in approximately 18 hours. Due to the Earth's curvature, it is impossible for a single satellite in low or medium Earth orbit to meet 90% coverage within the desired 12 hours.

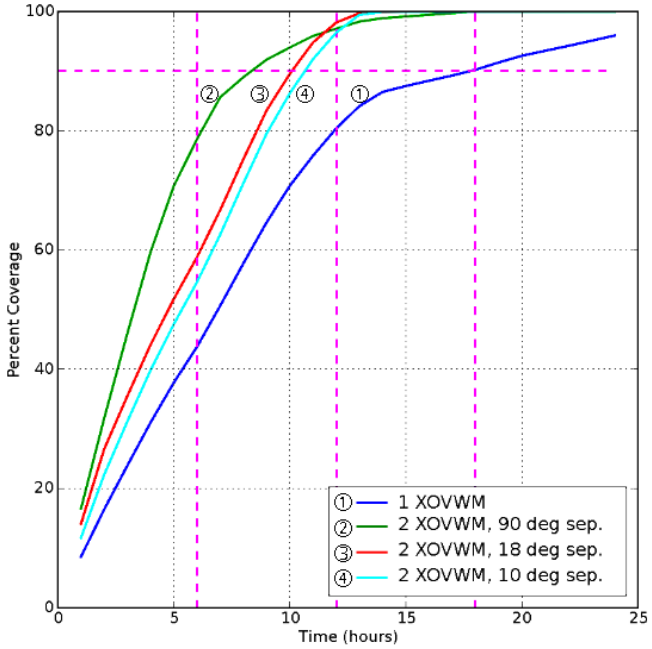
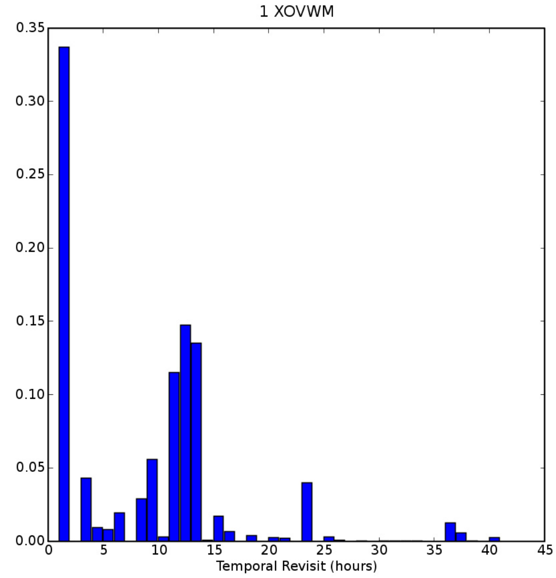


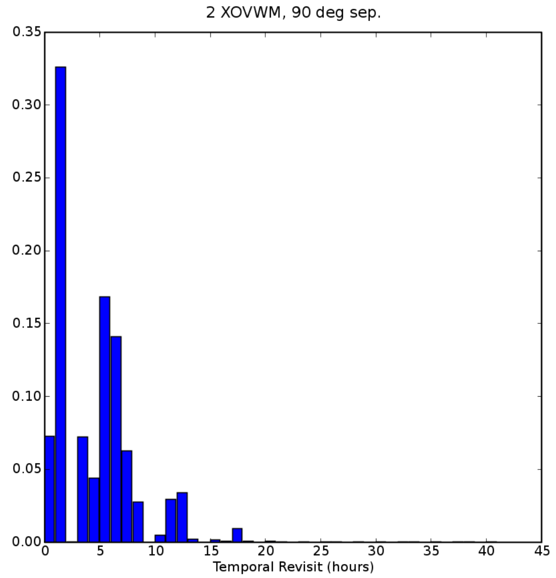
Figure 18: *Percentage of the Earth's surface covered for various satellite configurations as a function of time. The configurations shown are: (1) (blue) a single XOVWM (or QuikSCAT Replacement) satellite; (2) (green) two XOVWM satellites whose nodal crossing is separated by 90^o (optimal separation); (3) (red) two XOVWM satellites whose nodal crossing is separated by 18^o, so that the equatorial swaths are contiguous at the time origin; and (4) (cyan) two swaths separated by 10^o, so that they can share the same orbit plane. The threshold for 90% coverage is shown as a dashed horizontal line. Vertical lines indicate 6-hour, 12-hour, and 18-hour temporal separations. The performance of any of the constellation options easily meets the temporal coverage requirement of 90% coverage in less than 12 hours (Table 2).*

This temporal coverage limitation can be overcome by the use of two XOVWM satellites operating simultaneously at the same inclination, but with different nodal crossing times. The details of the temporal coverage will depend on the nodal crossings chosen. However, most two spacecraft configurations will lead to a coverage that exceeds the NOAA requirements. Figure 18 shows three such configurations. One configuration places the nodal crossings apart by 90^o and achieves 90% coverage in approximately 9 hours. Another possible configuration, which might be achievable with a single launch vehicle, thus reducing mission cost, would be to place the two orbits so that the swaths are adjacent at the equator, providing 90% coverage in approximately 10 hours. Finally, a configuration where the two satellites share the same orbit plane but are separated in time such that their nodal crossings are offset by about 10 degrees (which can be achieved with a single launch vehicle and minimal cost in consumables) achieves 90% coverage in a little under 11 hours.

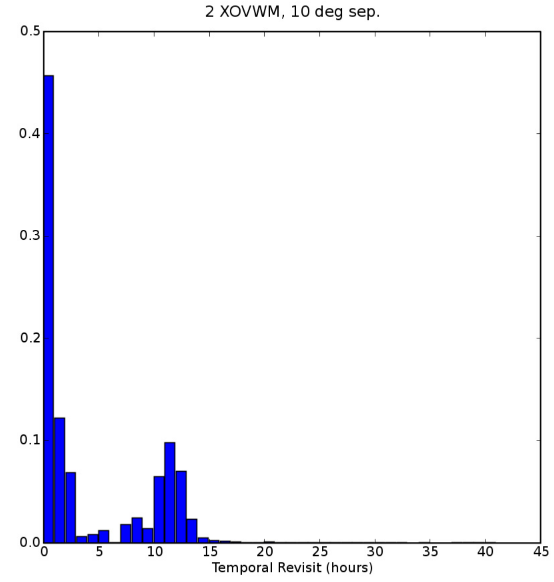
The global coverage fraction shown in Figure 18 is a required, but coarse, indicator of the temporal sampling characteristics of a spaceborne satellite or constellation. NOAA users are also very concerned about the typical intervals between observations, since these determine the ability to track moving weather features. Figure 19 shows the histograms for the revisit times for three of the configurations discussed above. It is clear from this figure that either of the two constellation options will provide more frequent and consistent temporal sampling than the single satellite solution. The figure also shows that the optimal configuration will lead to a typical spatial sampling that is much closer to 6 hours than to 12 hours. This ability to sample weather features nearly four times per day could have significant benefits to NOAA for both coastal, hurricane, and extra-tropical cyclone forecasting. The most cost-effective option, which uses a single-launch vehicle, would still meet the NOAA requirements, but has a typical sampling interval at mid- and low-latitudes, which is much closer to 12 hours.



(a)



(b)



(c)

Figure 19: *Distribution of revisit times for (a) one XOVWM satellite; (b) two XOVWM satellites whose nodal crossing is separated by 90^o (optimal separation); (c) two XOVWM satellites whose nodal crossing is separated by 10^o (most cost effective option). The single satellite option does not provide global uniform sampling characteristics due to coverage holes in the tropical regions. The optimal two satellite configuration (b) exhibits a large cluster of temporal revisits around 6 hours or less, which is the temporal sampling required to resolve semi-diurnal variations, a NOAA goal beyond the Level 1 requirements. A small residual cluster, due to tropical cross-overs, is centered around 12-hour revisits. The cost-effective option (c) still meets the Level 1 requirements, but a large part of the sampling is clustered around 12 hours, which is sufficient for sampling diurnal, but not semi-diurnal variations.*

Further study could determine the optimal orbit selection by trading between temporal coverage and mission cost (i.e., one launcher vs. two launchers). The present study has concentrated on determining a credible mission cost for the most conservative option, where the satellites are launched by separate launch vehicles with launch dates six months apart. This option minimizes the total mission risk by allowing the first system to be validated before the launch of the second one. However, if the long-term goal is to fly a constellation of satellites, the single launcher option becomes attractive as a mechanism to reduce the total life-cycle cost.

Section 6: Flight & Mission Implementation

A detailed Request for Information (RFI) was released to obtain spacecraft bus cost, schedule, and risk assessments from aerospace contractors based on the payload accommodation requirements developed as part of the study. Vendor responses indicated that the payload accommodation requirements for all options remain well within the capabilities readily available using existing spacecraft system designs and technologies. Low-risk, low-cost, heritage spacecraft bus designs can be scaled to accommodate either the QuikSCAT Replacement or Extended Ocean Vector Winds Mission (XOVWM) payload.

6.1 Spacecraft Bus Concepts

Based on the results of the instrument studies, a detailed RFI was prepared and released to the aerospace industry to obtain technical, schedule, cost, and risk information for suitable low-cost, low-risk, heritage spacecraft buses that could accommodate the XOVWM instrument concept. (Data provided to the contractors in the RFI is summarized in Appendix B; data requested from the contractors is summarized in Appendix C) The RFI responses are also applicable to spacecraft concepts for the other two options (QuikSCAT Replacement and XOVWM Constellation), with only minor adaptation. The QuikSCAT Replacement bus is scaled back slightly (e.g., smaller solar arrays, smaller batteries, smaller solid state recorder, and a reduction in attitude control components) given the lower mass and power consumption of its payload. The RFI responses also included cost estimates for the second flight system required for the XOVWM Constellation option.

Four aerospace contractors responded to the RFI. All demonstrated that they have the experience and capabilities to deliver one or multiple spacecraft buses to the XOVWM project, and that they have flight heritage/maturity, both in the spacecraft buses they proposed as the best matches to the capabilities required by the XOVWM mission, and in the additional flight hardware needed to meet XOVWM requirements. Each provided documentation to demonstrate having the necessary facilities and resources to fabricate, integrate, and test one or multiple buses of the XOVWM type.

Each contractor went through a design process in developing a spacecraft bus that met the mission and specific spacecraft requirements as defined in the RFI, leveraging experience from previous missions. Each contractor provided sufficient basis on their developed architecture to assess each design on its own, including detailed descriptions of margins against each of the technical resources. Each contractor provided a full block diagram of the spacecraft concept, as well as detailed information on the structures, attitude control, electric power system, propulsion, and command and data handling subsystems. The contractors' concepts were evaluated by the Jet Propulsion Laboratory's (JPL's) System Engineering Section and were deemed feasible for implementation.

Taken together, the responses demonstrate that cancellation of the instrument angular momentum is feasible, pointing requirements are achievable, and that data handling and storage is not an issue. All designs showed a power margin of >60%, and modifications to increase power capacity (for the XOVWM constellation second spacecraft) are feasible. Vendor responses provide sufficient information for preparing a complete Request for Proposal (RFP) that would be issued prior to any procurement activity. (This report contains only general information concerning vendor RFI responses to protect proprietary and/or competition-sensitive information, which requires restricted distribution.)

6.1.1 Spacecraft Configuration

The mechanical configuration of the spacecraft bus is optimized to provide an effective platform for the instrument and spacecraft subsystem. The design approach draws from low mass structural approaches used by past missions. The design is consistent with the science mission and all environmental conditions. The design is a structurally efficient bus frame and shear panel design. The design provides for a completely enclosed structure that forms the primary load path and also provides the necessary stiffness in all directions. Structural and thermal capabilities are easily tailored.

6.1.2 Thermal Control

Spacecraft bus thermal control is primarily passive with active heater control of selected components for all mission phases. Power dissipation and temperature limits of bus components are well understood. Key component placement will minimize temperature gradients, radiator area, and required heater power. The thermal design is highly flexible, primarily due to the large panel areas providing for large radiator area margins.

6.1.3 Electrical Power

The direct energy transfer architecture and the power control and distribution electronics have high heritage. By flying in the QuikSCAT heritage 6AM/6PM sun-synchronous orbit, the power system cost and complexity can be minimized. However, any sun-synchronous orbit can be easily accommodated with the proposed heritage designs.

6.1.4 Attitude Control

An important consideration in the design of the spacecraft bus is ensuring that the selected architecture meets instrument momentum and pointing requirements. The spacecraft pointing control architecture provides margin against the required instrument requirements using reaction wheels, gyros, and star trackers. On-board compensation of the instrument spin momentum uses nadir spin-axis momentum wheels. A magnetic momentum management system is selected for reaction wheel desaturation. The attitude control subsystem components leverage existing hardware and software interfaces to the proposed avionics and software designs.

6.1.5 Command & Data Handling

The electronics architecture is implemented with proven Electromagnetic Interference / Electromagnetic Compatibility (EMI/EMC) control methods in design and construction. The architecture consists of high heritage components employing power distribution units and a heritage processor, which supports the commanding, data handling, data storage (using a solid state recorder), and attitude control. The Command & Data Handling (C&DH) design accommodates a MIL-STD 1553 bus and RS 422 data interfaces.

6.1.6 Telecommunications

The telecommunications subsystem design is based on a reliable flight-proven design. It is not necessary to use gimbaled communications antennas; however, antenna placement and orientation is critical, given the large instrument reflector mounted on the nadir deck. The design uses an X-Band Consultative Committee for Space Data Systems (CCSDS) data downlink and S-band commanding. Link budgets show adequate system margins.

6.1.7 Propulsion

The design consists of a conventional monopropellant hydrazine system and involves propellant distribution, thrusters, and thermal control hardware, conceptually mounted on a dedicated structure. Propellant volume accounts for launch vehicle dispersions, orbit raising, orbit maintenance, and orbit lowering at end of mission.

6.1.8 Flight Software

The flight software will have significant heritage of core functions from previous missions. A high percentage of the existing software will be reused, and a low percentage of the code will be modified or newly developed. Anticipated modifications include changes to instrument data acquisition functions, addition of momentum cancellation control to logic models, and update of the device driver interfaces for the instrument.

6.1.9 Fault-Tolerant Design

The mission maximizes mission reliability using design simplicity, high-reliability parts, appropriate redundancy to mitigate design concerns, analysis, and testing. The requirements call for essential spacecraft functions to be fully redundant. Other hardware may have partial redundancy with provisions for graceful degradation.

6.2 Flight System Technical Margins

The XOVWM and QuikSCAT Replacement implementation concepts have been sufficiently characterized to determine technical resource requirements vs. the performance available from the spacecraft, launch vehicle. Ample margins in technical resources at the start of the development cycle provide for the management of risk. The margins for XOVWM are shown in Table 5. QuikSCAT Replacement margins are similar.

System margins calculations follow the methodology as prescribed in the JPL *Design, Verification/Validation and Ops Principles for Flight Systems (Design Principles)*.

Table 5: *Spacecraft bus technical resource margins are robust and consistent with good design practice.*

Performance Parameter	Conditions	Requirement	Performance	Margin
Mass (wet, includes contingency)	Mid-Range LV (Taurus II)	1215 kg	2250 kg	60%
Power	GaAs	>7.75 m^2	>10.4 m^2	>39%
Battery Capacity	Max 45% DoD	793 W-hr	1840 W-hr	~55%
Battery Cycles	Max 19% DoD	>26,000 cycles	100,000 cycles	4x
Uplink Margin	S-Band, 2 kbps	>3.0 dB	31.8 dB	28.8 dB
Downlink Margin, S-band	2 Mbps	>3.0 dB	16.8 dB	13.8 dB
Downlink Margin, X-band	25 Mbps	>3.0 dB	7.978 dB	+4.98 dB
On-Board Data Storage	2 days worth of data	162 Gb	256 Gb	~45%
Pointing Control Accuracy	Wind Observation Mode	0.1 deg (3 sigma)	0.08	~25%
Pointing Knowledge	Wind Observation Mode	0.01 deg (3 sigma)	0.005	~100%

NOTE: DoD = Depth of Discharge

6.3 Launch Vehicle

The Minotaur IV was originally identified as the preferred launch service, primarily for its low cost. For the RFI process, this vehicle tentatively established an envelope for performance, volume, and launch/ascent environments. Inquiries as to the feasibility of a Minotaur IV procurement were made in cooperation with NASA's Kennedy Space Center Launch Services Program Office (LSPO), which has been fully engaged in Minotaur IV considerations and has also been performing independent oversight activities for general use of the Minotaur IV as an alternative vehicle for other NASA missions. It was determined that a Minotaur IV could be procured through the Department of Defense (DOD) with funds directly released from the NOAA sponsor to the Space Development & Test Wing (SDTW) Rocket Systems Launch Program (RSLP).

Vendor RFI responses indicate that launch of the QuikSCAT Replacement mission on the Minotaur IV is feasible. XOVWM, although stowable within the Minotaur IV launch fairing (see Figure 20), does not have a sufficiently conservative mass margin for launch on a Minotaur IV. Medium-class launch vehicles are available, which would provide additional mass performance as well as a larger fairing volume. Trade studies can be performed early in the project lifecycle to support prudent launch vehicle selection.

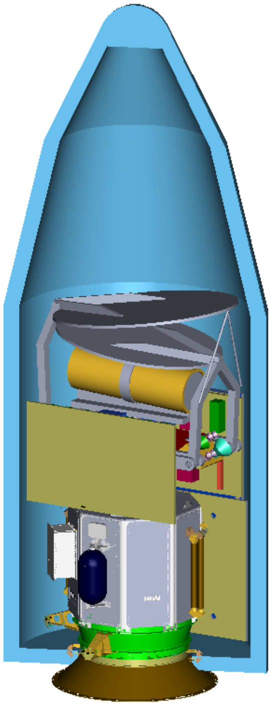


***Figure 20:** The XOVWM spacecraft with its primary reflector stowed for launch*

If two XOVWM spacecraft are used to reduce the revisit time as in the XOVWM Constellation option (see Section 5), a single Atlas V-501 vehicle using a dual-payload adapter currently under development by the United Launch Alliance could be used. Figure 21 shows two XOVWM spacecraft within a (conceptual) 5-m Atlas V dual-payload shroud. Preliminary analyses have shown that a two-satellite XOVWM constellation, which meets NOAA temporal sampling requirements, can be launched on a single Atlas V launch vehicle. In this configuration, the mass margin could permit additional propellant for rephasing the orbits to optimize ground revisit time. This approach is potentially more cost-effective than launching the two spacecraft on two smaller dedicated launch vehicles, and would be considered early in the project lifecycle.

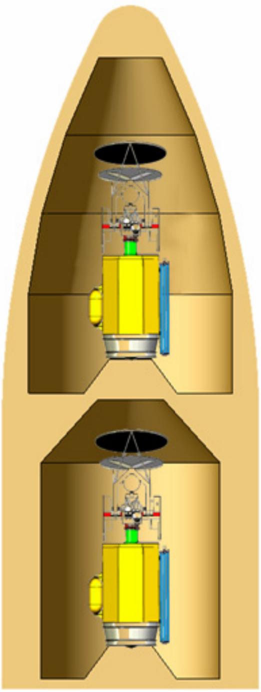


***Figure 21:** Two XOVWM spacecraft can easily be accommodated on a single Atlas V-501 launcher using a Type A 937-mm dual-payload adapter.*

6.4 Operations Concept

The NOAA Office of Satellite Operations (OSO) will operate the QuikSCAT follow-on mission. The operations tasks are mostly repetitive for scheduling the ground stations and sequencing the spacecraft to transmit recorded and real-time data, with an emphasis on low latency retrieval and data delivery. The NOAA Satellite Operations Control Center (SOCC) will perform the following tasks:

- Provide on-orbit command and control, data retrieval, health and safety monitoring, anomaly response, ground segment maintenance
- Support the launch and commissioning period

- Route instrument data to the Office of System Development Processing and Distribution (OSDPD) and JPL for near real-time processing
- Provide communication links from Command and Data Acquisition Stations (CDAS) and complementary stations to the National Oceanic and Atmospheric Administration (NOAA) Satellite Operations Facility (NSOF)

Ground stations at Fairbanks and Wallops will provide primary tracking, and OSDPD will develop the ground system to support the mission.

The Concept of Operations encompasses functions, data flows, interfaces, and operational scenarios. The basic system elements of the Ground Segment are the CDAS at Wallops, Virginia and Fairbanks, Alaska; the SOCC in Suitland, Maryland; real-time data processing facilities in the Environmental Satellite data Processing Center (ESPC); archive capabilities at the Comprehensive Large Array-data Stewardship System (CLASS); and NOAA's communications network. The National Polar-orbiting Operational Environmental Satellite System (NPOESS) Svalbard and McMurdo sites for data acquisition can potentially be included to achieve even lower data delivery latency. Cooperative agreements with the National Aeronautics and Space Administration (NASA) may add antenna sites at polar locations for backup and additional confidence for meeting the NOAA desired low data delivery latency. Figure 22 depicts the core operations system. The NSOF houses the control and data processing centers.

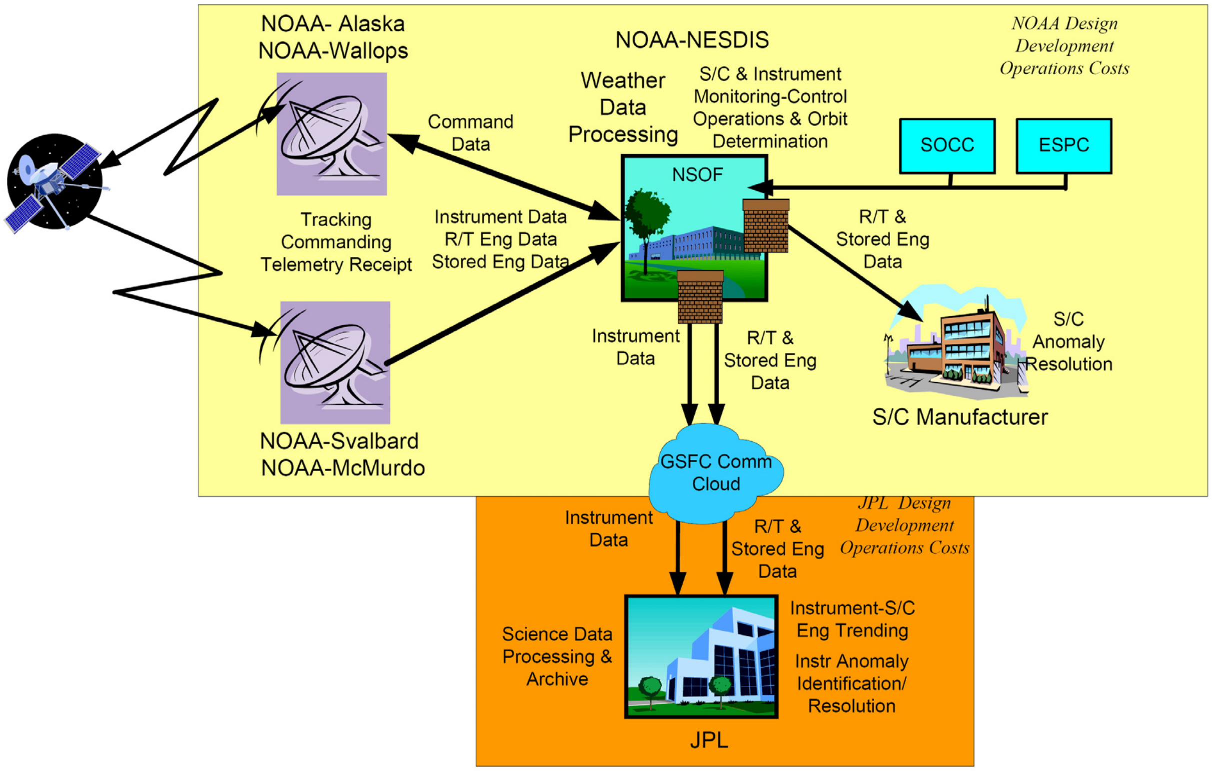


Figure 22: The core operations concept ensures reliable data return.

JPL will provide shadow processing for collaborative processing oversight, long-term instrument performance assessment, and engineering monitoring. The spacecraft provider will provide long-term engineering trend monitoring and anomaly resolution support. Communications networks for connectivity between the NSOF and GSFC will be provided by NOAA. JPL/NASA will provide the communications between the Goddard Space Flight Center (GSFC) and JPL.

Data delivery latency depends on: a) orbital period, b) tracking opportunities, c) tracking pass/downlink duration, and d) tracking site file preparation/communication duration from the tracking site to the NSOF. Half-orbit delivery latency is achieved with a northern hemisphere downlink at Alaska or Svalbard each orbit and a half-orbit additional downlink at McMurdo each orbit. Both northern stations are used daily to cover all orbits, while McMurdo provides southern hemisphere polar coverage for all orbits. For a downlink rate of 25 Mbps and communication rate from station to NSOF of 3 Mbps, the half-orbit delivery latency would be about 76 minutes for XOVWM.

Sequence command loads will be prepared as part of cyclical planning activities and uploaded to the spacecraft for weekly or semi-weekly regular operations. Spacecraft controllers will use manual commands to command the spacecraft to retrieve previous data when transmission noise or ground equipment malfunctions corrupt data or cause missed passes. All commands are encrypted before being sent to the transmitting station.

6.5 Ground Data Processing

JPL will have the full responsibility for developing the software and specifying the processing system for ESPC processing of backscatter measurements to derive ocean vector winds. JPL will assist with software checkout in the NOAA environment and will provide software and operations documentation. A version of the NOAA software will be run at JPL as a backup.

Processing software for both the QuikSCAT Replacement and XOVWM options will use the original QuikSCAT architecture. Some architectural changes may be needed for the input from NOAA file servers and output to the NOAA CLASS for archiving. NOAA's installation and use of the software will be patterned on that of the Ocean Surface Topography Mission (OSTM). The OSTM experience will provide a model for details of interfaces and needed operational features.

Processing steps are

- File receipt, acknowledgement, and logging
- Preprocessing to separate data types such as instrument science frames, spacecraft attitude and ephemeris, and ancillary data
- Initial processing for engineering unit conversion, calibration data, and instrument monitoring (Level 0 to Level 1A)
- Fundamental processing for Earth location and flagging and backscatter determination (Level 1A to Level 1B)
- Grouping of time-ordered backscatter measurements and radiometer (XOVWM) into spatially grouped cells for wind retrieval (Level 1B to Level 2A)
- Wind retrieval in each cell or region and determination of wind direction from areal analysis ("ambiguity removal") (Level 2A to Level 2B)
- Collection of metadata from processing steps for packaging and delivery to the archive

For the QuikSCAT Replacement case, there will be significant software reuse. For XOVWM, the architecture will isolate many changes to low level processing. However, significant new capabilities from the new data types will need to be exploited in wind retrieval processing. Nonetheless, QuikSCAT software will provide templates for implementation where the software cannot be used directly. Software development will also benefit significantly from pre-project work in simulation and science development.

The data volumes and processing required for XOVWM have been estimated based on the higher resolution measurements (approximately a factor of 25 over QuikSCAT at 12.5 km) and the increased number of data types. It is estimated that currently available multi-processing systems (approximately 64 nodes) can meet the throughput requirements.

Section 7: Risk Assessment

The conceptual design developed through the QuikSCAT follow-on study has been sufficiently characterized to evaluate all systems, subsystems, and key components for technical maturity. The implementation approach has been refined to minimize risk throughout the flight and ground segments. Identified risks have either been retired, or a plan has been developed to effectively manage and retire residual risk during the development process. The QuikSCAT follow-on mission options have low risk commensurate with an operational mission that will reliably deliver data to the National Oceanic and Atmospheric Administration (NOAA) user community.

7.1 Technology Maturity

The National Aeronautics and Space Administration (NASA) uses a nine-step scale of Technology Readiness Level (TRL) to assess of the maturity of a particular technology (see Appendix D for definitions). For a project to begin the formulation phase, all technologies should be either at TRL-6 (defined as "system/subsystem model or prototype demonstration in a relevant environment") or higher, or at TRL-5 (defined as "component and/or breadboard validation in relevant environment") with a clearly-defined path to mature the technology to TRL-6 by the preliminary design review. A subsystem is assigned TRL-6 if it is based on flight-proven design and technology, but requires redesign or modification in some manner to meet the specific requirements for the current application. TRL-6 elements do not require any further technology development or demonstration.

The flight systems for QuikSCAT Replacement and the Extended Ocean Vector Winds Mission (XOVWM) options have been defined and decomposed as shown in Table 6 below, in which key elements are identified with their corresponding TRL. Note that nearly all elements are at TRL-6 or higher. The sole TRL-5 element is the development and validation of a process for integrating the second mesh reflector surface into the deployable antenna assembly used for the XOVWM instrument; this can be accomplished as early as NOAA funding permits so that all system elements will be at TRL-6 or higher well in advance of the preliminary design review.

Table 6: *Maturity of instrument components is reflected in high Technology Readiness Levels*

Subsystem	Description	QS	XOVWM	TRL	Rationale
Spacecraft Bus	High heritage Earth Orbiter	✓	✓	9	All elements will be flight-proven designs. Vendor RFI responses suggest that either instrument option can be accommodated with relatively minor changes relative to existing spacecraft designs.
Spin platform	20-rpm rotating platform to support instrument electronics and antenna. Provides data and power interfaces to spacecraft.	✓	✓	6	Design uses existing technology. All elements are based on flight-proven components and designs.
	• *Motor, bearings, data/power slip rings, and speed control electronics*	✓	✓	*6*	*Design uses existing technology that is flight-proven on WindSat/Coriolis.*
	• *Spin platform with integrated instrument RF electronics and antenna*	✓	✓	*6*	*Design uses existing technology that is flight-proven on WindSat/Coriolis, AMSR/ADEOS II, AMSR-E/Aqua, and SSMI/DMSP.*
	• *Launch restraint mechanism*	✓	✓	*9*	*Uses flight-proven mechanisms.*

Subsystem	Description	QS	XOVWM	TRL	Rationale
Radar Electronics	Scatterometer systems	✓	✓	6	Design uses existing technology. All elements are based on flight-proven components and designs.
	• *RF electronics, digital subsystem and power*	✓	✓	*6*	*Uses flight-proven components.*
	• *Ku-Band TWTA*	✓	✓	*8*	*Pulsed helix TWTA completed flight qualification testing for NASA OVWM project.*
	• *C-Band TWTA*		✓	*6*	*Same technology as the Ku-Band TWTA.*
Radiometer	X-Band polarimetric radiometer		✓	6	Design uses existing technology that is flight-proven on JMR and flight qualified for AMR radiometers (Jason and OSTM missions).
Antenna subsystem	Deployable 3.5 m by 5.0 m elliptical, dual-sided, parabolic mesh reflector		✓	5	All elements based on flight-proven technology and components. Current TRL 5, driven by maturity of second mesh surface, will be raised to TRL 6 with prototype testing prior to PDR, and to TRL 8 prior to integration with spacecraft.
	• *Deployable perimeter truss reflector with front side mesh surface*		✓	*6*	*Design uses existing technology scaled from flight-proven 9-m and 12-m designs.*
	• *Second mesh surface*		✓	*5*	*Design uses existing technology. Mechanical & thermal modeling / analysis demonstrated the required surface tolerance is readily achievable. Assembly process will be demonstrated with prototype prior to PDR to achieve TRL 6.*
	• *Deployment mechanism*		✓	*6*	*Design uses existing technology based on flight-proven mechanism used on 9-m and 12-m designs (5 of 5 successful deployments).*
	• *Launch restraint release mechanism*	✓	✓	*9*	*Uses flight-proven mechanisms.*
	• *20 openings per inch (OPI) gold plated molybdenum mesh*		✓	*6*	*Same material is flight-proven in 10 OPI mesh. Measured RF properties of 20 OPI mesh meet XOVWM specifications.*
	• *Secondary reflectors. Deployable 2 m by 1.4 m elliptical, planar, composite reflector*		✓	*6*	*Design uses existing technology, materials and processes, including flight-proven release and deployment mechanisms.*
	• *Ku-band feed horns. Overlapping transmit and receive feed horns for low scan loss*		✓	*6*	*Design uses flight-proven materials and processes. Prototypes have been fabricated and the measured radiation patterns meet XOVWM specifications.*
Antenna	1-m solid reflector with integrated Ku-band feeds	✓		9	Build to print flight-proven reflector used for the SeaWinds instrument

A primary focus for the Jet Propulsion Laboratory (JPL) study team has been to mitigate risks associated with the XOVWM concept so that a low risk implementation approach can be followed. In May 2007, the team prepared a concept review presentation and involved JPL scientists and engineers, NASA Ocean Vector Winds Science Team members, and NOAA operational users in a full day review of the mission concept. The review panel unanimously endorsed the concept and provided feedback to the team. A discussion of the key issues, including mitigation actions as well as future plans, is provided in the following sections.

7.2 Antenna

The QuikSCAT Replacement scatterometer antenna is identical to that already flown on QuikSCAT. The reflector would be build-to-print, using QuikSCAT drawings. The two Ku-band feeds would also be identical to those used on QuikSCAT and can be readily fabricated.

The XOVWM antenna is new, but leverages heritage from communications satellites. The XOVWM antenna subsystem consists of a deployable reflector, deployable secondary reflectors, feeds, and spin mechanism. From a performance viewpoint, feed design and main surface distortion were identified early in the study as the largest risk items. A detailed physical optics simulation of the antenna has been developed to assess overall antenna performance. The simulation has used both an ideal surface and a surface with worst-case mechanical and thermal distortions. Comparisons of calculations with ideal and distorted surfaces have shown that the effects of distortion on the antenna performance are well within requirements. Another performance concern for the reflector was the radio frequency (RF) performance of the mesh for the X-band radiometer; a very reflective surface is needed for accurate radiometry. Mesh reflectivity was evaluated using a radiometer that viewed the sky via reflection from manufacturer-supplied mesh samples. X-band reflectivity was found to be quite high, with emissivity correspondingly low (less than 0.5%). Feeds were also identified as a risk item, so early work has been completed to demonstrate feasibility and retire the associated performance risk. Because the optimal beam spacing requires the feeds to be "overlapped" since fully separated feeds would generate beams with spacing that is too large, a novel overlapped feed design was created and verified by finite element simulation. The simulated feed pattern was tested in the full physical optics simulation with excellent results. Next, the design was fabricated (see Figure 23) and tested and the measured feed patterns were used in the full reflector simulation, again with good results. This prototyping effort has demonstrated the feasibility of the overlapped feed design and retired performance risk associated with the feeds.

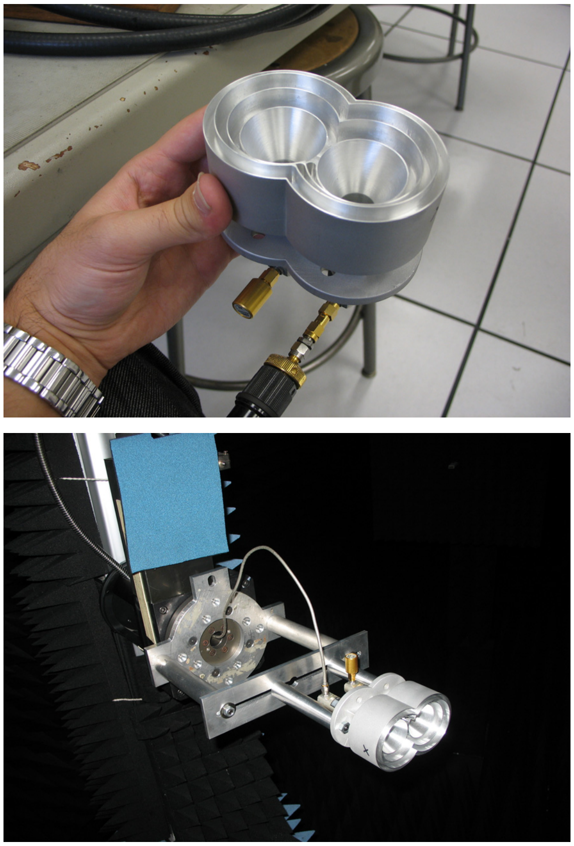


Figure 23: *Overlapped transmit/receive feeds for XOVWM*

From a mechanical deployment viewpoint, the secondary reflectors are considered low risk. These are simply flat plates with spring-damper, self-deploying hinge mechanisms that latch into a stiff preloaded state once deployed. The stowed reflectors are held in place by launch locks that are released on-orbit.

The main reflector is considered to be a larger risk. However, numerous mesh antennas of this size and larger have been deployed in space, primarily for use in satellite communications. There are currently 33 successfully operating in orbit in unclassified missions and only one reported failure. There are likely additional, classified missions with successfully deployed antennas. Although a two-sided mesh has yet to be flown, the changes relative to the one-sided antenna are modest. Specifically, the existing one-sided antenna already uses a back-to-back net support structure. Hence, it can be made two-sided with small mass increase simply by installing mesh behind both front and back nets. This is considered to be an engineering modification of the existing reflector rather than a new technology development. Another potential risk is the use of a highly elliptical reflector. The 3.5 m x 5 m XOVWM reflector is more elliptical than previously built reflectors; however, the ellipticity is considered to be within the current design envelope. Again, the modifications are an engineering modification rather than a technology development.

To retire risks associated with the main reflector, several tasks should be performed as soon as possible. A dual-sided reflector will require that a new assembly sequence be developed to integrate the second mesh surface. The new assembly process will be demonstrated by building a flight-like prototype. That prototype can be exercised through repeated stow and deploy cycles to verify repeatability. The surface accuracy will be evaluated by photogrammetry. Successful completion of these steps will achieve TRL-6.

7.3 Spinning Platform

For all of the QuikSCAT follow-on mission options studied, apart from some controller electronics on the spacecraft, the entire instrument is a spinning system. The spin mechanism is a critical component because it keeps the instrument spinning at a constant rate (18 rpm for QuikSCAT Replacement; 20 rpm for XOVWM) for the operational life of the observatory. Previous missions with large antennas (e.g., WindSat) have already demonstrated suitable mechanisms. While these instruments have had lower spun masses, their spin rate is significantly larger than the spin rate planned for the QuikSCAT follow-on mission. WindSat, for example, has a lower spun mass than XOVWM (less than half) and a spin rate of 32 rpm, so that the momentum for WindSat is only about 20% less than that of XOVWM.

Other functions of the spin mechanism include:

- Electrical slip rings to transfer all power and data across the rotating interface
- Stable velocity control and high resolution angular position knowledge
- Structural support for the entire instrument while rotating

To verify the feasibility of a spin mechanism able to provide the required functions and performance, a request for information (RFI) for the spin mechanism was issued. RFI responses from three spin mechanism manufacturers have shown the feasibility and availability of a spin mechanism for a QuikSCAT follow-on. The RFI responses also indicated that slip rings can accommodate the 150+ lines needed for data and power for XOVWM. Lessons learned from WindSat were considered in the proposed spin mechanism designs. Spacecraft vendors have verified the feasibility of providing the required momentum compensation.

Spin mechanisms in space have a long history, with dozens having been built over the last three decades. Reliability has been demonstrated by long-term on-orbit operation, as well as lifetime testing of bearings and slip rings on the ground. The 5-year operational lifetime of a QuikSCAT follow-on mission is well within the capability of current spin mechanism technology; spin mechanism capabilities required for XOVWM or QuikSCAT Replacement do not require new technology or substantial re-design of existing systems.

7.4 Real-Time Processor

The QuikSCAT follow-on uses field programmable gate array (FPGA)-based on-board processors. The QuikSCAT Replacement processor would implement essentially the same algorithm as used in QuikSCAT; however, an FPGA is used in place of the obsolete FFT-chip used on QuikSCAT. The XOVWM processor will implement a more computationally intensive algorithm. A preliminary XOVWM processor algorithm has been implemented in floating point. An assessment of the expected number of arithmetic operations has allowed a preliminary design of the onboard processor.

Early in Phase A, the processing algorithm developed as part of this study will be translated from floating point software into a hardware description language, such as Verilog or VHDL. This description of the hardware will then be accurately simulated using commercially available packages. The next step will implement the design of the algorithm in the chosen FPGA architecture and validate operational robustness.

7.5 Ku- and C-Band TWTAs

Traveling Wave Tube Amplifiers (TWTAs) have been used to produce the Ku-band radar transmitter signal for the NSCAT and SeaWinds scatterometers developed at JPL. TWTA technology for this application is flight-proven and the devices are exceptionally reliable. The Ku-band TWTA that is planned for either the QuikSCAT Replacement or XOVWM instrument is manufactured by Thales Electron Devices in Ulm, Germany and is flight qualified having completed environmental qualification testing in accordance with JPL requirements. Because the Ku-band TWTA is an existing, qualified design, the technical risk for this element is very low.

A C-band radar transmitter meeting the same basic functional and performance requirements as the existing Ku-band TWTA is needed for the XOVWM instrument. At C-band frequencies it is possible to generate the required pulsed RF power using either TWTA technology or solid state power amplifiers (SSPAs). For the ASCAT instrument, a C-band SSPA has been operating successfully on-orbit. However, because the power efficiency of TWTAs is higher, and because it is possible to adapt the existing Ku-band TWTA for the C-band application, the TWTA is a lower technical risk and has been selected as the baseline. Thales has confirmed that a C-band TWTA is available from their existing product line and that the device can be easily modified to include a grid for pulsed operation and integrated with the same basic high voltage power supply as is used for the Ku-band TWTA. The reconfigured C-band TWTA would complete environmental qualification testing at Thales before the XOVWM flight units are delivered to JPL. Because of the similarity to the flight qualified Ku-band TWTA, the modified C-band TWTA is a low technical risk element.

In order to mitigate the schedule risk associated with these long lead items, this procurement will be initiated as early as possible.

7.6 Instrument Redundancy Design

Driving requirements for a QuikSCAT follow-on mission include a minimum lifetime of 5 years, due to the operational nature of the mission. To meet this requirement, the design approach is to eliminate all credible single-point failures. Furthermore, failures should result in graceful degradation of system performance.

For the QuikSCAT Replacement option each instrument subsystem has a spare: digital, RF electronics, power distribution, and TWTA. Each spare can be switched (via ground command) into the system independently of the state of the other subsystems. Both beams are powered by the same TWTA, with pulses alternating between beams. The XOVWM scatterometer has four Ku-band beams and two C-band beams, each powered by a TWTA. The hardware associated with a given beam is single string, so that failure of a single beam reduces performance but allows the mission to proceed. Assemblies common to all beams are redundant and individually selectable, like the QuikSCAT replacement; these include the RF electronics back end, digital electronics, and unit supplying common power.

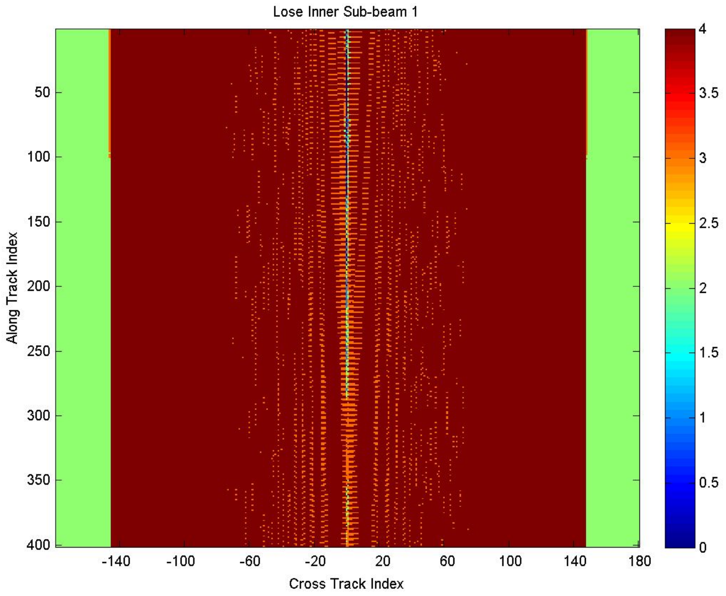


***Figure 24:** XOVWM coverage when an inner beam is lost. Color scale is number of measurement directions.*

Simulations of the XOVWM system were performed to verify that the plan to make beams single string is acceptable within the philosophy of requiring failures to result in graceful degradation of performance. By simulating the loss of one or more Ku-band beams, we were able to quantify the effects on retrieval performance. When a single inner or outer beam is lost, the percentage of cells with two direction measurements is the same as with all beams working. The sum of cells with three of four direction measurements is also the same. However, the percentage with three directions increases while the percentage with four directions decreases. Figure 24 shows the effect of single or multiple beam loss on coverage. The orange cells near the center have lost a direction measurement. The effects of the loss of one beam on wind retrieval results in a very small degradation of the retrieved wind (see Figure 25). Furthermore, loss of even two

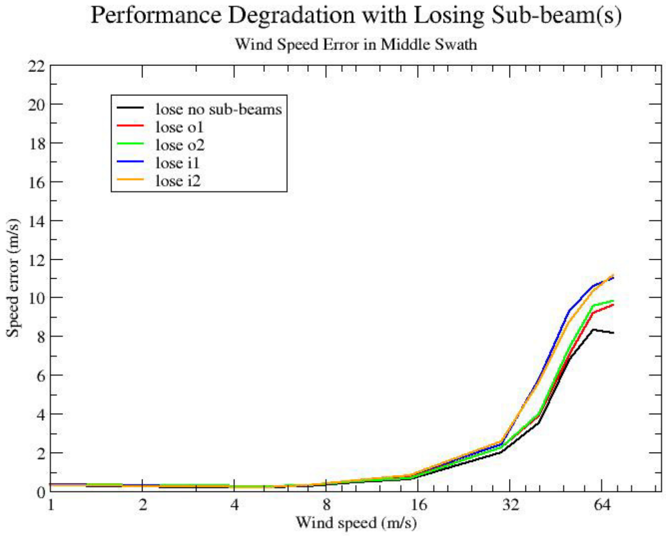


***Figure 25:** Wind speed error versus wind speed for all beams working and for various beam loss scenarios.*

beams results in minimal impact if one beam is an inner and the other an outer (one beam lost from each side of the antenna). When both Ku-band beams on a given side are lost, the effects are more severe. All cells have a maximum of two direction measurements, and the outer swath is lost if the outer beams fail. The situation is very similar at C-band, since each side initially has only one beam. In summary, the simulations show that the XOVWM design is tolerant to loss of a single beam and is even tolerant to loss of two beams in some cases.

7.7 Thermal Control

One driving technical trade for the early development of the instrument design was the location of the high power components (spun vs. despun side). From a thermal perspective, placing the high power components on the spun side adds complexity as radiators are not in a fixed orientation relative to the orbit; however, it is desirable for other reasons, and so significant work was done to develop a thermal model and baseline thermal architecture to further examine the implications of this early configuration trade decision. A thermal analysis was performed to determine whether spun-side avionics could be thermally accommodated. Subsequent work showed this was indeed feasible using a low-risk passive thermal control architecture. A baseline thermal design was developed in which components are directly mounted to two advanced pyrolitic graphite (APG) radiators; the use of APG has been extensive in JPL missions and is considered low-risk relative to other technologies.

7.8 Spacecraft Bus Technology Maturity

While the XOVWM payload demands more spacecraft resources due to higher mass, power, data rate, and momentum compensation requirements than the QuikSCAT Replacement option, the payload accommodation requirements for both options are well within the capabilities readily available using existing spacecraft system designs and technologies. Vendor RFI responses suggest that by relying on existing heritage spacecraft buses, either option can be accommodated with low-risk, high heritage, fault-tolerant designs consistent with the conservative risk posture and with only modest differences in cost. Furthermore, as the spacecraft is specified to allow operation in any sun-synchronous orbit at 800-km altitude, an XOVWM constellation can be easily implemented.

Section 8: Cost Estimation

A grass-roots cost estimate for the three mission options was prepared, using a detailed work breakdown structure (WBS) and input from experts from all relevant engineering and programmatic disciplines. An Independent Cost Estimate was performed by the Aerospace Corporation to validate the internal estimate. There is substantial agreement between the two methods (within 4%). The cost estimates were also validated by an independent cost review that concluded that they were complete, credible, and ready for submission to National Oceanic and Atmospheric Administration (NOAA), giving high confidence that the mission can be implemented on schedule and within budget.

8.1 Methodology

The study team developed a grass roots estimate for each of the three options. General guidelines including the WBS, scope of work, deliverables, master schedule, mission objectives, mission duration, and other information were provided to the cost estimators for each performing organization. Each estimator documented the assumptions, scope of work, and plans for the assigned tasks and prepared an estimate. The cost estimates include labor, procurements, travel, services and other direct costs for the entire mission life cycle. For major subcontracted items, rough-order-of-magnitude (ROM) estimates were obtained from qualified vendors. For other procurements, material costs were estimated by scaling the actual costs for similar systems. The raw cost estimates were entered into the Jet Propulsion Laboratory (JPL) standard cost estimating tool (Project Cost and Analysis Tool), which applies the JPL-approved planning rates and factors to each direct cost element and provides cost summaries by WBS element for analysis and planning. The study team members along with their division management completed detailed reviews of the estimates to resolve inconsistencies and make corrections and refinements as necessary.

The study team has worked with counterparts within NOAA / National Environmental Satellite, Data, and Information Service (NESDIS) to define organizational responsibilities regarding planning for mission operations, the development of data processing and processing facility capabilities, and other work that will be required during the development phase as well as responsibilities associated with the operation of the flight system during the operational phase of the mission life cycle. Estimates of the life cycle costs for work that will be performed by NOAA have been prepared by NOAA, but are not included in the cost estimates submitted in this report.

To validate the JPL grass-roots estimate, Aerospace Corporation was enlisted to prepare an independent cost estimate (ICE). An analogy approach using historical data from similar projects as well as cost models were used. Cost adjustments for technical and programmatic differences are factored in. A cumulative probability distribution of life cycle costs was determined, and the 70th percentile value was compared with the grass-roots estimate.

Before finalizing the cost estimates, the study team presented details of the cost estimates to a review panel, including the division management for each performing organization, as well as experts from outside JPL. NOAA representatives participated in the cost review as well. The consensus of the review board was that the cost estimates are complete, credible, and ready for submission to NOAA, subject to specific recommendations, which have been incorporated in this report.

8.2 Assumptions and Basis of Estimate

The cost estimates are based on the organizational responsibilities, WBS, and assumptions shown in Table 7, Figure 26, and Table 8, respectively.

***Table 7:** Organizational Responsibilities*

JPL	NOAA	NASA	USAF
• Project Management • Safety and Mission Assurance • Project System Engineering • Develop wind retrieval algorithms and data processing code • Instrument: – Design – Manage subcontracts – Instrument I & T – Instrument operations sustaining support – Instrument test bed • Manage spacecraft system contract: – Spacecraft bus – Observatory I & T – Launch ops support – Mission ops dev. support – Mission ops sustaining support – Flight system test bed • Develop mission operations concept and planning • Lead on-orbit calibration and validation campaign	• Develop mission operations planning • Perform mission operations • Operations facilities • Ground stations and ground network • Contribute to wind retrieval algorithms • Data processing facilities • Process, deliver, and archive data products	• Launch services for XOVWM (funded by NOAA)	• Minotaur IV launch services for QuikSCAT Replacement (funded by NOAA)

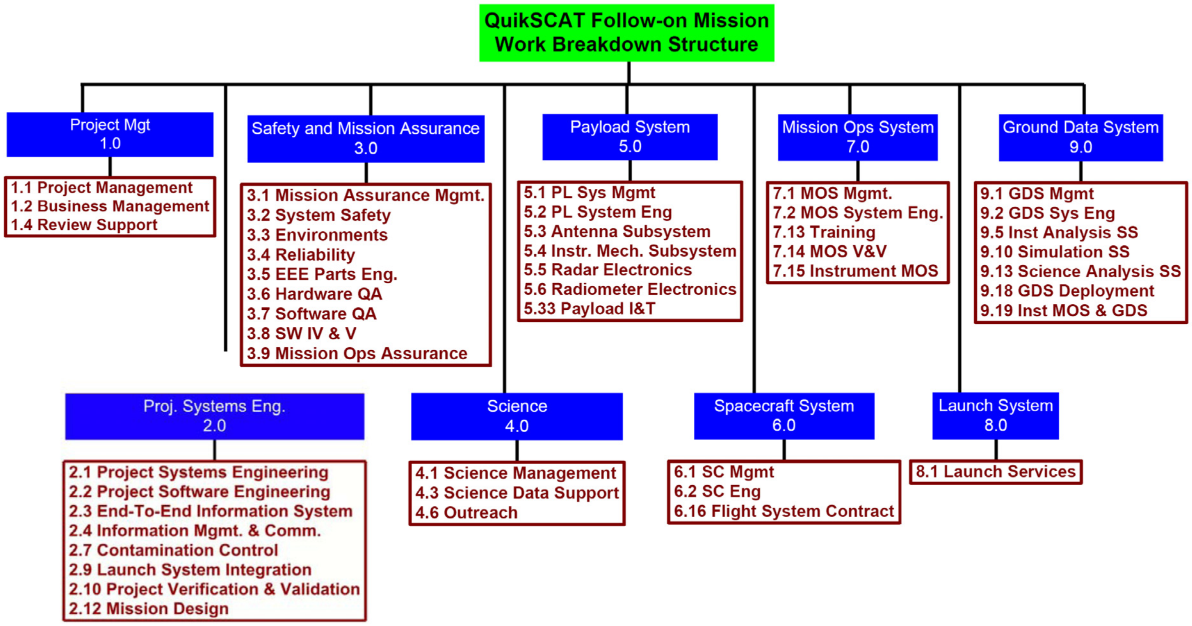


***Figure 26:** QuikSCAT Follow-on Mission Work Breakdown Structure*

Table 8: *Basis of Estimate and Assumptions*

Subject	Basis of Estimate and Assumptions
Organizational Responsibilities	• As specified in the previous table
Development Approach	• Project is a NASA reimbursable flight project funded by NOAA • Implementation conforms with NASA/JPL project life cycle • JPL Flight Project Practices and design principles apply • Earned value management begins at start of phase C • Detailed implementation plans and approach for each WBS element are defined by each performing organization • Mission critical elements are block redundant; other elements may use functional redundancy with graceful degradation • Development hardware (breadboards, prototypes and EM) are included • Flight spare hardware is included • Flight system and instrument test beds are included
Spacecraft	• Cost and schedule are based on RFI responses from four qualified suppliers • JPL insight/oversight costs are based on recent experience and technical division staffing guidelines
Launch Vehicle	• Minotaur IV (QuikSCAT Replacement) cost ($32 M) is based on information provided by USAF • Medium class launch vehicle (XOVWM) cost ($77 M) is based on NASA SMD guidance on pricing assumption for post Delta II launch services supplied by the NASA Launch Series Program (LSP)
Payload	• RFI responses for primary reflector and spin mechanism • Recent ROM pricing for Ku- and C-band TWTAs and SeaWinds 1-m reflector (for QuikSCAT Repl.) • Scatterometer system costs are based on: - Defined technical baseline for the instrument concepts - JPL in-house designs for recently built, similar instruments - FPGA firmware implementation for digital processor • X-band polarimetric radiometer based on specific changes to JPL's advanced microwave radiometer (AMR) instrument design
Algorithms and Data Processing	• Algorithms and processing code are developed by JPL • NOAA supports algorithm and model function development • Processing facilities are supplied and operated by NOAA
Mission Operations (5-year duration)	• Developed jointly by JPL, NOAA, and the spacecraft contractor • Spacecraft is commissioned by contractor and delivered to NOAA to operate at Launch + 30 days • Operations facilities, ground stations, and ground network are all supplied by NOAA • JPL and the spacecraft contractor provide sustaining support throughout phase E
Development Schedule	• XOVWM schedule is 59 months from start of phase A through launch (53 months for QuikSCAT Replacements) • Second launch is 6 months after the first (XOVWM Constellation) • Payload development schedule is 48 months through delivery to spacecraft integration & test (I&T) (42 mo. for QuikSCAT Repl.) • Funded schedule margin complies with JPL Flight Project Practices
Current JPL Planning Rates and Factors are used (effective October 2007)	• Other NASA costs for reimbursable tasks are based on those negotiated for other large recent reimbursable projects at JPL
Budget Reserves	• Reserves are allocated to each WBS element in accordance with risk and maturity assessments • The total reserves complies with JPL Flight Project Practices
Note: Costs for work performed by NOAA are not included in the estimates contained in this report	

8.3 XOVWM Master Schedule

The project master schedule for a single XOVWM system with a launch readiness date of February 2013 is shown in Figure 27. Having completed pre-phase A studies, including risk mitigation actions, the XOVWM concept is ready to begin Phase A immediately. With appropriate funding, the XOVWM development can be completed in 59 months to provide an operational system to support the 2013 hurricane season. The second XOVWM flight system would be scheduled to launch 6 months after the first system in August 2013. The development cycle for the QuikSCAT Replacement option is 53 months and could be launched as early as August 2012.

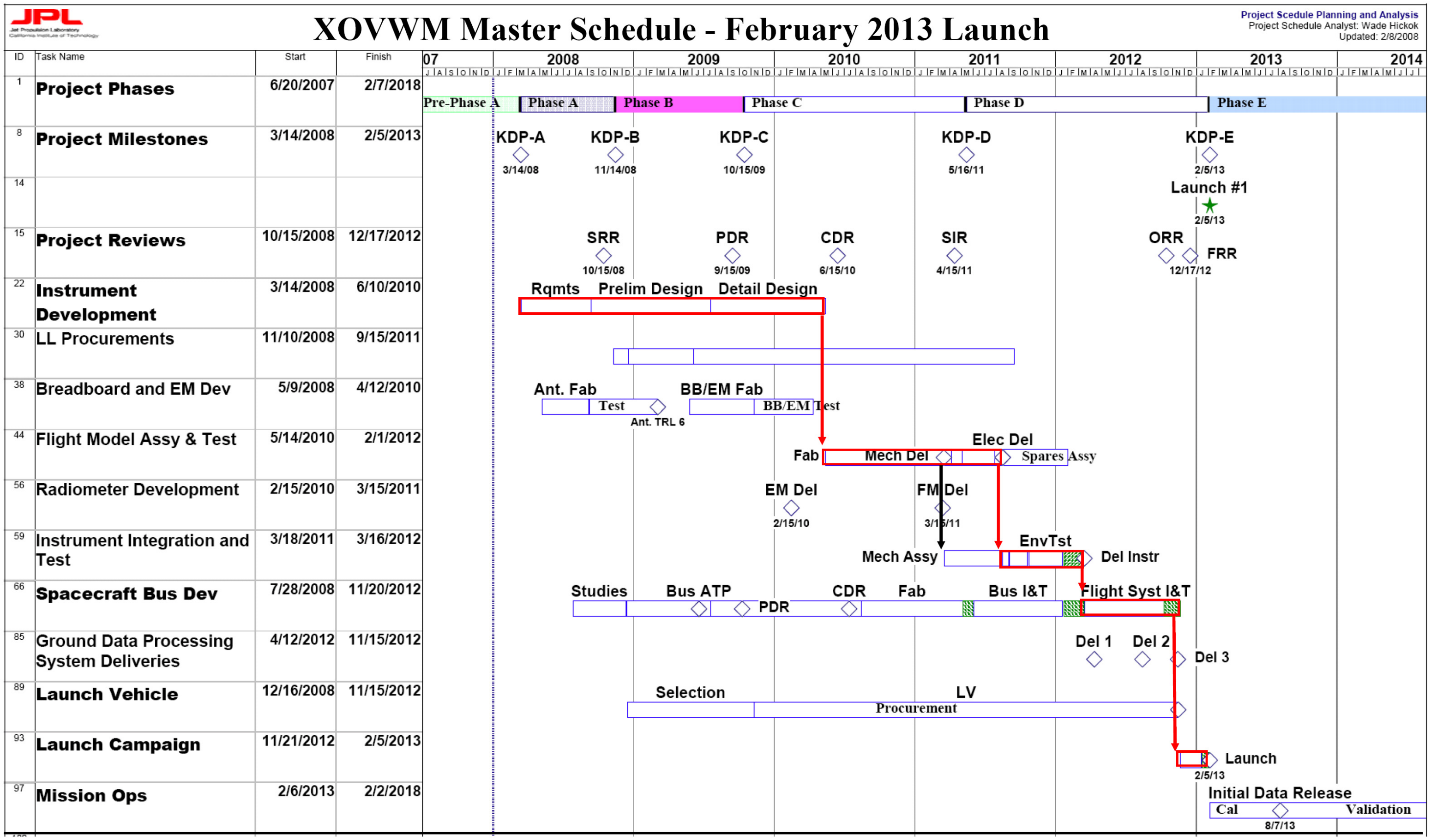


Figure 27: Project master schedule for a single XOVWM system (February 2013 launch)

The study team recognizes that funding availability may control how rapidly the mission can be implemented and has therefore developed an alternate master schedule that is consistent with the funding limitations defined by NOAA/NESDIS ($1.5M, $3.0M, $70M in FY08, FY09, and FY10 respectively) (Figure 28). In this case the first XOVWM system can be launched in October 2014 with the second system for the constellation launching in April 2015. The QuikSCAT Replacement option could be launched April 2014.

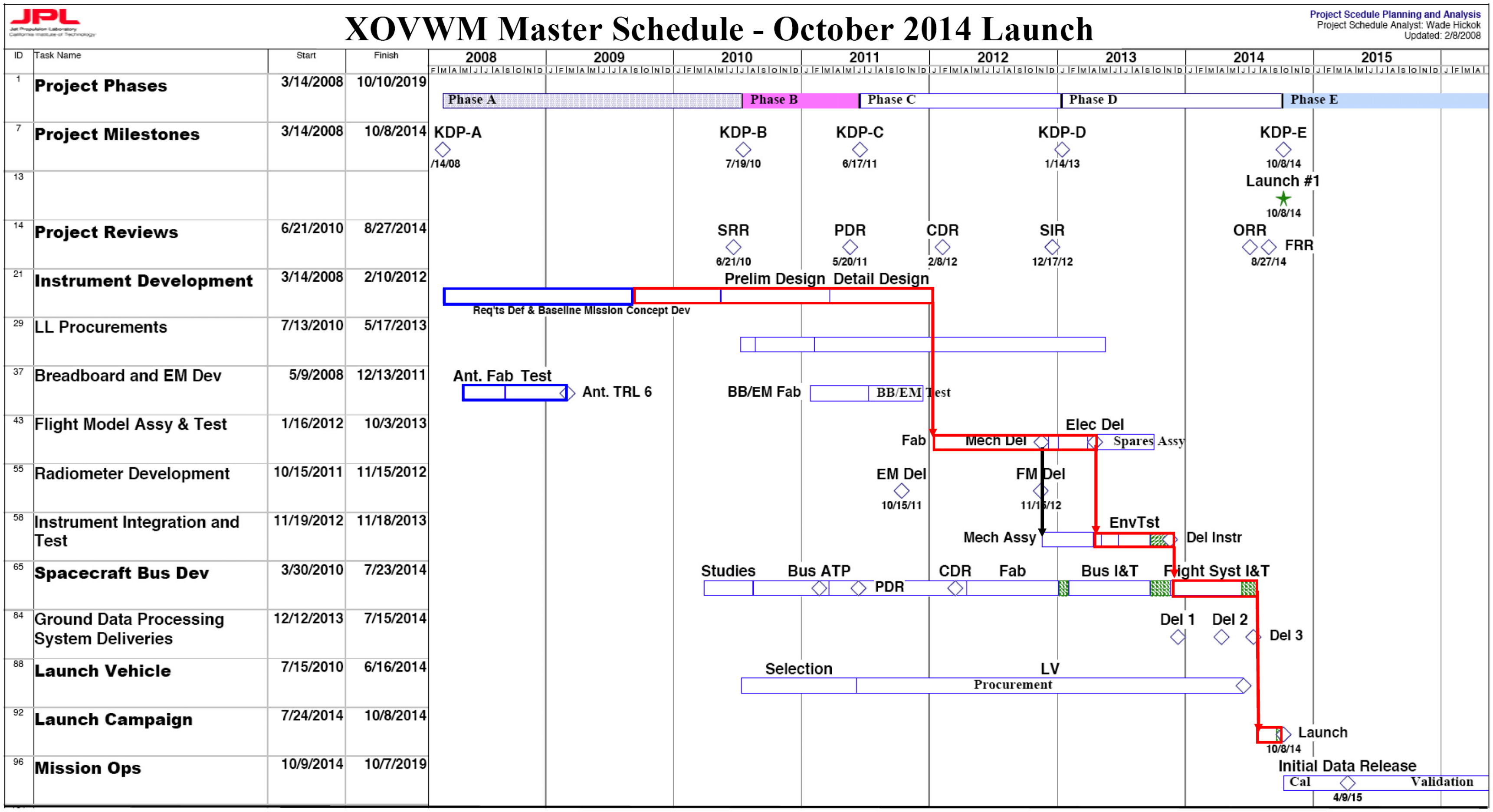


Figure 28: Alternate XOVWM master schedule (October 2014 launch)

8.4 Cost Estimates

The cost estimates in FY08 dollars for each of the three options are shown in Table 9. The cost for work that will be performed by NOAA is not included in these estimates. The independent cost estimates developed by the Aerospace Corporation are shown for comparison (Table 10). (See Appendix E for more detail on the Independent Cost Estimate.) In all cases the project grass-roots estimates are within 4% of the independent estimates. The QuikSCAT Replacement mission and XOVWM, options 1 and 2 respectively, each include a single spacecraft with five years of operations support. The XOVWM constellation, option 3, includes two spacecraft launched within six months of each other with five years of operations support for each. The costs presented here are based on the best information presently available, including non-binding budgetary estimates from suppliers. The estimates are appropriate for budget planning, but do not represent a binding cost commitment by JPL.

Table 9: *Cost comparison (in FY08 fixed-year dollars) of QuikSCAT Replacement, XOVWM, and XOVWM Constellation*[*]

Cost Element	Options (FY08 $M)		
	1	2	3
	QuikSCAT Replacement	XOVWM	XOVWM 2 S/C Constellation
Phases A–D			
Management, System Engineering, & Mission Assurance	$30.1	$34.5	$40.8
Science	$4.7	$7.3	$8.5
Payload	$91.6	$161.1	$208.8
Spacecraft Bus	$86.8	$91.4	$142.1
Mission Operations	$3.3	$4.4	$5.0
Data Processing System	$5.6	$13.5	$13.8
Subtotal	$222.1	$312.2	$419.0
Reserve	$66.2	$92.0	$125.9
Phase A–D Subtotal	**$288.3**	**$404.2**	**$544.9**
Phase E			
On-Orbit Calibration/Validation	$2.8	$3.5	$4.6
Mission Operations	$9.4	$10.6	$13.2
Subtotal	$12.2	$14.1	$17.8
Reserve	$1.8	$2.1	$2.7
Phase E Subtotal	**$14.0**	**$16.2**	**$20.5**
Launch Vehicle	$32.0	$77.0	$154.0
Other NASA Costs	$1.9	$2.4	$3.3
JPL Total	**$336.2**	**$499.8**	**$722.7**

Table 10: *Aerospace Corporation cost estimates*[*]

Cost Element	Options		
	1	2	3
	QuikSCAT Replacement	XOVWM	XOVWM 2 S/C Constellation
Aerospace Corp. ICE (FY08 $M)	$325.5	$510.5	$729.5
Percent difference	-3.2%	2.1%	1.0%

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[*] The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

8.5 Funding Profiles

The funding profiles in real year dollars for the full life cycle of each option are shown in Table 11. JPL forward planning rates and factors are used in the conversion from FY08 dollars to real year dollars. Funding for work that will be performed by NOAA is not included in these profiles.

Table 11: *Funding profiles for full life cycle of each option (in real-year dollars)*[3]

Fiscal Year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	Total
Option 1 (RY$M) QuikSCAT Replacement LRD April 2014	1.5	3.0	49.9	103.5	154.1	63.6	15.3	4.6	3.5	3.0	2.8	0.6							405.4
Option 2 (RY$M) XOVWM 1 Spacecraft LRD February 2013 (Earliest Launch Date)	10.7	117.2	200.0	141.0	61.3	18.6	4.5	3.4	2.8	2.7	0.5								562.7
Option 2 (RY$M) XOVWM 1 Spacecraft LRD October 2014	1.5	3.0	68.2	153.5	174.2	110.7	79.2	6.9	4.2	3.0	3.0	1.4							608.7
Option 3 (RY$M) XOVWM 2 Spacecraft Constellation LRD Oct. 2014 and April 2015	1.5	3.0	68.0	196.0	254.2	187.3	142.5	23.1	4.8	3.7	3.1	2.3	0.3						890.0
Option 3 (RY$M) XOVWM 4 Spacecraft Constellation LRD Oct. 2014 and April 2015 with replacements 5 years later Note: Assumes independent build-to-print of a second set of two spacecraft.	1.5	3.0	68.0	196.0	254.2	187.3	142.5	280.9	307.3	214.3	119.2	22.9	14.2	6.2	4.7	4.0	3.0	0.4	1,829.6

NOTE: LRD = launch readiness date

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[3] The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

Section 9: Summary

Three mission options for continued provision of operational ocean surface vector winds data (QuikSCAT Replacement, Extended Ocean Vector Winds Mission [XOVWM], and XOVWM Constellation) were evaluated. All options are technically feasible. Detailed cost estimates have been developed and independently validated. While a QuikSCAT Replacement option would continue current operational measurement capabilities, there is a strong and clearly defined operational need for improved capabilities in high winds (e.g., hurricanes or extra-tropical cyclones), heavy precipitation, and near coasts to enable significantly improved severe storm and coastal hazard forecasts, which are provided only by the XOVWM options.

The National Oceanic and Atmospheric Administration (NOAA) user impact study unambiguously recommends proceeding with a XOVWM mission start as soon as is feasible. The XOVWM mission concept is mature, uses existing technology, and is ready for an immediate Phase A mission start to support operations as early as the 2013 hurricane season, depending on funding availability.

Section 10: References

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Appendix A: Abbreviations & Acronyms

ADC	Analog to Digital Converter
AMR	Advanced Microwave Radiometer
AMSR/ADEOS II	Advanced Microwave Scanning Radiometer - Advanced Earth Observing Satellite
AMSR-E/AQUA	Advanced Microwave Scanning Radiometer - Earth Observing System
APG	Advanced Pyrolitic Graphite
ASCAT	Advanced Scatterometer
CBE	Current Best Estimate
C&DH	Command and Data Handling
C/C	Spacecraft
CCSDS	Consultative Committee for Space Data Systems
CDAS	Command and Data Acquisition Station
CDAS	Ground Segment are the Command and Data Acquisition Stations
CLASS	Comprehensive Large Array-data Stewardship System
C-MAN	Coastal-Marine Automated Network
DOD	Department of Defense
DoD	Depth of Discharge
EEE	Electronic, Electrical, and Electromechanical
EM	Engineering Model
EMI/EMC	Electromagnetic Interference/Electromagnetic Compatibility
ESPC	Environmental Satellite data Processing Center
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FPGA	Field Programmable Gate Array
FY	Fiscal Year
GDS	Ground Data System
GFDL	Geophysical Fluid Dynamics Laboratory
GMF	Geophysical Model Function
GSFC	Goddard Space Flight Center
ICE	Independent Cost Estimate
I&T	Integration & Test
IV&V	Independent Verification & Validation
JAXA	Japanese Aerospace Exploration Agency
JMR	Jason Microwave Radiometer
JPL	Jet Propulsion Laboratory
LRD	Launch Readiness Date
LSP	Launch Services Program
LSPO	Launch Services Program Office
LV	Launch Vehicle
MBPS	Megabits/second

MHz	Megahertz
MIC	Microwave Integrated Circuit
MOS	Mission Operations System
NASA	National Aeronautics and Space Administration
NESDIS	National Environmental Satellite, Data, and Information Service
NIC	National Ice Center
NOAA	National Oceanic and Atmospheric Organization
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NRC	National Research Council
NRL	Naval Research Laboratory
NSCAT	NASA Scatterometer
NSOF	NOAA Satellite Operations Facility
NWP	Numerical Weather Prediction
NWS	National Weather Service
OPC	Ocean Prediction Center
OPI	Openings per Inch
OSDPD	Office of System Development Processing and Distribution
OSO	Office of Satellite Operations
OSTM	Ocean Surface Topography Mission
OSVW	Ocean Surface Vector Winds
PDR	Preliminary Design Review
PL	Payload
PM/SE/MA	Project Management, System Engineering, & Mission Assurance
QuikSCAT	Quick Scatterometer
RF	Radio Frequency
RFI	Request for Information
RFP	Request for Proposal
RMS	Root Mean Square
ROM	Rough Order of Magnitude
SAR	Synthetic Aperture Radar
SDTW RSLP	Space Development & Test Wing Rocket Systems Launch Program
SEU	Single Event Upset
SOCC	Satellite Operations Control Center
SRAM	Static Random Access Memory
SSMI/DMSP	Special Sensor Microwave/Imager - Defense Meteorological Satellite Program
SSPA	Solid State Power Amplifier
SW	Software
TPC/NHC	Tropical Prediction Center/National Hurricane Center
TRL	Technology Readiness Level
TWTA	Traveling Wave Tube Amplifier

USAF	United States Air Force
VHDL	VHSIC Hardware Description Language
WBS	Work Breakdown Structure
WFO	Weather Forecast Office
WRF	Weather Research and Forecasting Model
XOVW	Extended Ocean Surface Vector Winds
XOVWM	Extended Ocean Surface Vector Winds Mission
XPR	X-band Polarimetric Radiometer

Appendix B: Data Provided to Spacecraft Contractors

Key Attributes	XOVWM Specification
Radar Characteristics	Radar frequencies: Ku-band at 13.4 GHz and C-band at 5.25 GHz Radiometer frequency: X-band 10.65 GHz
Mass	The instrument current best estimate is of 320 kg (CBE). This number does not include contingency. The instrument current uncertainty is of 30%. In the deployed configuration, the center of mass is 2.9 m off the nadir spacecraft deck and along the spin axis. At the center of mass, the rotary moments of inertia are: 137 kg*m^2 about the spin axis and 274 and 302 kg*m^2 perpendicular to the spin axis.
Power	The instrument requires a steady state power throughout the orbit of 782 W (CBE). The instrument carries a 30% uncertainty against the CBE.
Volume	(Specific drawings provided for deployed and stowed volumes and configuration)
Data Rate	Continuously operated. The Instrument data rate is 1 Mbps (200 Mbps raw SAR with onboard instrument processing).
Thermal Control	Current design thermally isolated at spacecraft mounting surface
Pointing Requirements	The Spacecraft Bus shall provide 3-axis nadir pointing during operations as follows: a) Control 0.1 deg 3-sigma, per axis b) Knowledge accuracy within 0.01 deg, 3-sigma, per axis
Antenna	5 meter by 3.5 meter (elliptical shape) high frequency dual AstroMesh Deployable Reflector
Antenna Spin Rate	The antenna spin frequency is of 20 rpm. The spin axis is in the nadir direction. Comment: The spin axis is through the center of the instrument platform.
Electrical Interfaces	1553B command and telemetry, w/ RS-422 for Science telemetry
Orbit	The spacecraft shall be compatible with a sun-synchronous 800-km circular orbit with a local equator crossing time at the ascending node of 6:00 A.M.
On-Orbit Mission Life	The spacecraft shall be capable of operating on-orbit for 5 years minimum. The spacecraft shall accommodate consumables for 10 years
De-Orbit	End-of-mission plans shall include the depletion of energy sources and reduction of the post mission orbital lifetime to fewer than 25 years.
Launch Vehicle	The spacecraft shall be compatible with a Minotaur IV.
Launch Vehicle Capability	The combination of the spacecraft bus mass and the instrument, as well as any required interface adapter between the LV and the spacecraft bus and expendables, and adequate margins, must be within the performance envelope of the launch vehicle. The spacecraft contractor is free to offer options for injection strategies to achieve the 800-km operational orbit.
Launch Vehicle Adapter	The non-separating payload adapter will be 62-inch diameter.
Reliability	Essential spacecraft functions should be fully redundant. Other hardware may have partial redundancy with provisions for graceful degradation, or may be functionally redundant. The EEE parts quality shall meet or exceed NASA GSFC, EEE-INST-002, level 2.
Momentum Compensation	The spacecraft shall be capable of compensating for the angular momentum generated by the instrument rotating antenna. Comment 1: It is the intent to deliver a balance instrument, i.e., c.g. on rotation axis & inertia cross product close to zero. However, some small residual imbalance will exist. Comment 2: A spin-up and spin-down strategy will need to be worked in the future with the instrument team.
Instrument Deployment	The spacecraft shall provide ordnance actuation signals to unlock the spin table, as well as primary and secondary reflectors.
Physical Requirements	The instrument does not require any volume on the spacecraft bus at this time. However, the spacecraft shall provide what volume could be made available for instrument boxes.

Key Attributes	**XOVWM Specification**
Data Collection	Downlink is required at least once per orbit to NOAA CDA & IPO ground stations, preferably twice per orbit to minimize delivery latency. The spacecraft shall provide storage capability for 2 days of data with down-link capability of two orbits of data in a single pass.
Data Flow	Communications with the spacecraft will be via S-band for real-time engineering telemetry at 2, 4, or 16 kbps, and 2 kbps command uplink. X-band downlink at 25 Mbps will be used for down linking stored engineering and instrument data from the two-day capacity spacecraft SSR.
Data Format	CCSDS

Appendix C: Data Requested from Spacecraft Contractors

Key Attributes	XOVWM
Technical	Spacecraft bus technical description and heritage. Show a top-level block diagram highlighting heritage and any new developments. Spacecraft heritage discussion should include hardware, software, experience, design heritage, ground support equipment, flight spares, etc., and rationale for any changes. Provide an assessment of the flight system resources (mass, power, etc.), including justification for flight system contingency used. Identify additional design considerations, additional hardware, and sensitivity to and impact of design for higher instrument mass/power/data-rate to understand design drivers and sensitivity to changes. Also include a discussion on software technical description and heritage, redundancy description, and spares philosophy.
Schedule	Spacecraft development schedule and earliest possible launch based on technical developments, assuming a project start date (ATP) of October 2009.
Cost	Total flight system ROM costs in Real Year dollars, broken down by flight elements, including a discussion of: • Basis of cost estimate • Proposed cost margin and basis • Annual (government fiscal year) phasing of funding requirements, consistent with the development schedule Cost estimates should also include the costs for: • Integrating and testing the instruments with the spacecraft • Integrating the spacecraft with the launch vehicle • Launch campaign • Checkout/commissioning period of up to 30 days.
Second Spacecraft	Cost estimates for a second spacecraft, to be launched six (6) months after the first spacecraft has launched. The second spacecraft will have the same capabilities as the first and support the same instrument design.
Risk	Risk assessment, including top risks and mitigation plans.
Other Considerations	Identify any drivers for cost (technical and/or programmatic), suggestions for requirements relaxation, or improvement in instrument design that would result in significant bus or mission cost savings and/or risk reduction.

Appendix D: NASA Technology Readiness Levels

For a lengthier discussion of NASA Technology Readiness Levels (TRL), see http://www.hq.nasa.gov/office/codeq/trl/trl.pdf.

Level:	***Criterion:***
TRL 1	Basic principles observed and reported
TRL 2	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept
TRL 4	Component and/or breadboard validation in laboratory environment
TRL 5	Component and/or breadboard validation in relevant environment
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
TRL 7	System prototype demonstration in a space environment
TRL 8	Actual system completed and “flight qualified” through test and demonstration (ground or space)
TRL 9	Actual system “flight proven” through successful mission operations

Appendix E: Independent Cost Estimate

An Independent Cost Estimate (ICE) was performed for the XOVWM mission (including the second flight unit option), as well as a QuikSCAT Replacement mission. This was performed by the Aerospace Corporation, primarily by cost analogies to assess the total life cycle cost. The second unit was estimated using benchmarks based on historical data, suggesting that it would cost 43% of the first, including launch and operations.

The ICE estimates for all three options agreed with project estimates to within 4%. This correlation is excellent for this point in the project life cycle, suggesting that there is low cost risk associated with any of the options.

QuikSCAT Replacement Option ICE Cost Comparison[*]

Category (Cost in FY08 $M)	Independent Estimate	Project Estimate	Difference ($M)	Difference (%)
PM/SE/MA	$28.31	$30.15	$(1.84)	-6.09%
Science/Ground	$15.59	$13.60	$2.00	14.68%
Payload System	$98.03	$91.51	$6.52	7.12%
Spacecraft System	$69.13	$88.48	$(19.35)	-21.87%
Reserves	$68.19	$66.20	$1.99	3.01%
Total Development	**$279.26**	**$289.94**	**$(10.68)**	**-3.68%**
Launch System	$32.00	$32.00	-	0.0%
Phase E	$14.25	$14.25	-	0.0%
Total Mission	**$325.51**	**$336.19**	**$(10.68)**	**-3.18%**

XOVWM Mission ICE Cost Comparison[*]

Category (Cost in FY08 $M)	Independent Estimate	Project Estimate	Difference ($M)	Difference (%)
PM/SE/MA	$43.79	$34.33	$9.46	27.57%
Science/Ground	$27.20	$25.03	$2.18	8.70%
Payload System	$166.27	$161.12	$5.16	3.20%
Spacecraft System	$77.05	$93.56	$(16.51)	-17.65%
Reserves	$102.50	$92.10	$10.40	11.30%
Total Development	**$416.82**	**$406.12**	**$10.69**	**2.63%**
Launch System	$77.00	$77.00	-	0.00%
Phase E	$16.66	$16.66	-	0.00%
Total Mission	**$510.48**	**$499.78**	**$10.69**	**2.14%**

XOVWM Constellation Option Two Satellite ICE Cost Comparison[*]

Category (Cost in FY08 $M)	Independent Estimate	Project Estimate	Difference ($M)	Difference (%)
PM/SE/MA	$57.56	$40.89	$16.67	40.76%
Science/Ground	$34.01	$27.32	$6.69	24.49%
Payload System	$207.17	$208.99	$(1.82)	-0.87%
Spacecraft System	$119.53	$145.26	$(25.72)	-17.71%
Reserves	$136.59	$125.49	$11.11	8.85%
Total Development	**$554.87**	**$547.94**	**$6.92**	**1.26%**
Launch System	$154.00	$154.00	-	0.00%
Phase E	$20.66	$20.66	-	0.00%
Total Mission	**$729.52**	**$722.60**	**$6.92**	**0.96%**

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[*] The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.