

Nanosats for Radar Altimetry

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ABSTRACT

Radar altimeters such as TOPEX/Poseidon and Jason-2 measure the sea surface height as well as wave height and wind speed, providing key information about the ocean. The U.S. Navy previously launched the Geodesic Satellite (GEOSAT) and the GEOSAT Follow On (GFO), and has considered developing other missions. Small and micro satellite designs have been proposed by Johns Hopkins University Applied Physics Laboratory¹, Surrey Space Center² and Thales Alenia Space³. A 6U CubeSat concept was proposed by Australia's Defense Science and Technology Organization⁴. The Navy invested in a Small Business Innovative Research effort to develop a radar altimeter payload for a 3-unit CubeSat⁵.

Radar altimetry data feeds various ocean models to predict large scale currents and other phenomenon. These ocean models have been custom built to account for the specifications of each altimetry satellite. While nanosats may be capable of radar altimetry, it is likely they will not provide the same level of accuracy as larger satellites. The impact of less accurate data on ocean modeling must be understood prior to investing in a micro or nanosatellite radar altimetry mission.

In January 2015, Program Executive Office Space Systems, the Space and Naval Warfare Command's Systems Center Pacific and the Naval Research Laboratory began a study to evaluate the impact of nanosatellites on ocean modeling. The accuracy of a possible 6U radar altimetry design was estimated. The resulting performance of an ocean model was characterized. Finally, the cost-effectiveness of the mission was examined. This paper summarizes the results of the study⁶.

CURRENT RADAR ALTIMETRY OF THE SEA SURFACE

Predicting the ocean environment requires continual observations at appropriate spatial and temporal scales. Space based altimeter-observed sea surface height to date remains the critical source that enables ocean prediction throughout the globe.

Measuring and predicting the ocean environment is crucial to Navy battlespace awareness in addition to Meteorological and Oceanographic (METOC) forecasting. It requires continual observations at appropriate spatial and temporal scales. Space-based sea surface altimetry is a key component, in part due to the ability to enable prediction of ocean currents on a global scale.

Ocean surface currents directly impact search-and-rescue operations and mine warfare (i.e. surface drifters). Moreover, currents and associated ocean circulation processes influence both METOC operations and battlespace awareness capabilities from the surface to the undersea domain. A prime example is acoustic propagation.

Nadir-viewing radar altimeters such as Topography Experiment (TOPEX)/Poseidon and Jason-2 measure sea surface topography, as well as wave height and wind velocity. The next mission, another United States and CNES (French space agency) collaboration called Jason-3, will launch in 2015. The European Space Agency has plans for launching two altimeter-bearing satellites; Sentinel-3A will launch in July 2015, and Sentinel-3B will launch in 2016. These will both have radar altimeters.

ALTIMETRY CALCULATIONS

An altimeter instrument provides an accurate measurement of the transit time of a radar pulse emitted by the satellite, reflected by the ocean surface, and returned to the satellite. The satellite hardware usually employs several techniques to allow having a small ocean footprint simultaneously with a small transmitter/receiver antenna and a low power requirement. The reader is referred to the material by Chelton et al.⁷, which provides a thorough analysis and treatment of this subject. The rate of radar pulses emitted by the altimeter instrument is referred to as the pulse repetition frequency (PRF), which is an important property to determine the sensor accuracy. If the satellite moves at least one antenna length between pulses, the specular reflectors on the ocean surface returning radar energy to the satellite are independent between pulses. Thus, errors in range due to the small number of specular reflectors are independent between pulses. To reduce the error in range estimation, Jason-2 uses a PRF of 2 KHz, and samples are averaged over 1 second intervals resulting in observations every 6.5 km along the ground track.

The area of ocean measured is ideally larger than wind-driven waves and ocean swell but smaller than typical large-scale ocean features, which range from twenty to thousands of kilometers. The radar pulse footprint varies in size depending on the satellite altitude and the ocean wave height. The higher ocean waves reflect the radar pulse further from the sub-satellite point. In calm seas, the ocean area reflecting the radar pulse has a diameter of about 3 km, and this increases up to 10 km in areas with waves of 15 m amplitude for the TOPEX/Poseidon altimeter. This is the across-track footprint size. Temporal averaging elongates the footprint in the along-track direction.

The altimeter measures the range between the satellite and the ocean surface from the round-trip travel time of a radar pulse. Knowledge of the satellite distance relative to a reference ellipsoid allows computation of the sea level, and knowledge of the geoid provides the sea surface height.

POTENTIAL IMPACT OF NANOSATS

Studies have demonstrated that increasing the number of satellite altimeter observations leads to greater accuracy in forecasting the mesoscale features as measured by sea surface height (SSH)^{8,9}. Associated features affecting surface radio frequency ducting are also more accurately predicted with additional satellite observations¹⁰.

Single platform altimetry measurements have fundamental limitations. Consider estimating the two-

dimensional SSH structure based on observations from a single satellite. Spatial de-correlation scales of the ocean are about the Rossby radius of deformation, which varies from 100 km at mid-latitudes to 10 km at high latitudes. Two issues must be considered: 1) the error level of individual observations, and 2) the spatial coverage of observations.

At a small scale, SSH is relatively constant. If N observations are obtained, and the errors in the observations are independent, the error in the SSH estimate in a small location is proportional to $1/\sqrt{N}$. Thus, the sensor error level impacts SSH estimation at each small observation point.

Within a period of one second or a distance of 6.5 km along the ground track, Jason-2 emits about 2060 radar pulses. With a 1.5 m diameter antenna, the maximum number of pulses for uncorrelated errors in this distance is about 4333. For a single traditional altimeter satellite, increasing PRF or reducing system noise provides no new information on the two dimensional structure of ocean features, and the improved accuracy has little impact. Investing in continually reducing error levels of a single satellite provides diminishing returns.

To decrease error levels in the two-dimensional structure, additional information along different satellite ground tracks is required. The cost of adding a traditional altimeter satellite is relatively large. Thus, it is difficult to extend the basic ocean space observational capability using a traditional altimeter satellite. Providing more spatial observations of separate ocean features, even with higher error levels, offers the potential for increased return on investment.

Nanosats offer the potential for a small investment to result in significantly improved ocean observations. Nanosats are much lower cost than traditional altimeter satellite systems. This allows a relatively small investment to provide in a fielded satellite system. In addition, because the nanosat is not constrained to sample in the same ground track as existing altimeters, it may obtain ocean information that is independent from other altimeter satellites. However, nanosats may provide lower accuracy data, since a nanosat bus provides much lower power to altimeter, which resulted in a reduction in the PRF. If we reduce power consumption roughly by a factor of 4, PRF is reduced by a factor of 4 and RMS error is increased by a factor of 2. By a simple scaling argument, to reduce the present Jason-2 altimeter power consumption of 70 W to 1 W, the PRF would be reduced to about 30 Hz. The sensor error level increases from 2 cm to about 16.7 cm. This tradeoff is countered by nanosat's use of the latest

generation of electronics, which employs significant advancements in power efficiency, signal processing and receiver noise mitigation. Application of nanosats for ocean altimeter observations necessitates considerations involved in the tradeoffs between accuracy and quantity of observations across independent ocean features.

In addition to power constraints on the altimeter sensor, nanosats have limited space, weight and power to accommodate additional sensors to correct for atmospheric and ionospheric conditions. These include the total electron count required for the ionosphere propagation error and the brightness of temperature due to total precipitable water vapor. Thus, atmospheric and ionospheric models may be used as sources of this information, and errors in the model estimates must be considered.

STUDY METHODOLOGY

The study consists of three main efforts: (1) evaluate a nanosat altimeter reference design and estimate performance; (2) simulate the output of the ocean model for a range of potential nanosat altimeter error levels; (3) conduct a cost-effectiveness analysis.

Reference Design

The nanosat altimeter reference design is created based on the existing science & technology efforts at PEO Space Systems (PEO SS). The performance of the design is estimated and provided to the ocean model. Major performance metrics are the radar range error and orbit determination error. Monte-Carlo analysis is used to determine the likely performance envelope of the system. Details of the reference design and performance predictions are described in section 2.3.

Since a nanosat altimeter has not yet been demonstrated, it is necessary to simulate a range of possible noise levels. Simulated noise for the nanosat altimeter is added to the sampled nature run. The noise is modeled by a zero-mean Gaussian random variable, at three different values of standard deviation. The noise model is uncorrelated from one ground track point to another. For the simulated Jason data, an RMS noise level of 2 cm is used in all simulations. The nanosat noise standard deviation levels simulated are 10.5 cm, 22.5 cm and 40.5 cm.

Ocean Model Simulations

The numerical model for the study is the Navy Coastal Ocean Model (NCOM). To understand the possible scope of a nanosat constellation, we will construct simulated data using 2, 4 and 6 nanosats in a coordinated set of orbits. The ground tracks are based

on the GEOSAT-Follow On (GFO), the Environmental Satellite (ENVISAT), Jason-1 and TOPEX-interleaved ground tracks. A prior numerical model experiment is used as a reference and is referred to as the 'nature run'. The model results cover from June 1994 through December 1995. During this time, the GFO, ENVISAT, Jason-1 and TOPEX-interleaved altimeter missions were all operating. The data from the four satellites constrains the nature run as closely as possible to the real ocean. The simulation results have been compared to in situ observations to ensure the nature run is accurate and is documented¹⁰. The nature run provides the full 3D time evolving fields needed to evaluate potential nanosat constellations. For a given nanosat configuration, the nature run SSH is sampled along the ground tracks. The mean SSH from the nature run over the 1.5 years must also be computed and removed from the observations to provide sea surface height anomaly (SSHA), which is the processed information from the altimeter satellite.

It is assumed that a traditional altimetry satellite in the Jason orbit will be flying concurrently with the nanosats. Therefore, all experiments include sampling along the Jason ground track. One experiment uses only the simulated Jason data and serves as a reference to determine value added of different nanosat constellations and noise levels. Each constellation (2, 4, 6 nanosats) and each noise level (10.5, 22.5 and 40.5 cm) is simulated resulting in nine experiments plus the one experiment using Jason only.

Cost-Effectiveness

The team determines the cost-effectiveness of nanosats for a radar altimetry program. The analysis follows the process established in Mroczek's "Determining the Cost-Effectiveness of Nano-satellites"¹¹.

NANOSAT RADAR ALTIMETER

Previous Small Altimeter Concepts

The smallest altimeter mission known to fly in space is "Altika," a 65 kg payload on the Satellite with Argos and Altika (SARAL). The mission was a collaboration between France and India, and launched in 2013¹². Small satellite altimeter designs have also been considered by the Johns Hopkins University (JHU) Applied Physics Laboratory (APL)¹, Surrey Space Center² and Thales Alenia Space³. A 6U CubeSat concept was proposed by Australia's Defense Science and Technology Organization⁴.

SBIR N122-146 Radar Altimeter

PEO SS solicited "Novel CubeSat Payloads for Naval Space Missions" under Small Business Innovative

Research (SBIR) topic N122-146 in June 2012⁵. The intent of the research effort was to create new naval payloads using the existing 3-unit (3U) Cubesat bus designed by the JHU APL for the Vector Joint Capability Technology Demonstration (JCTD). PEO SS awarded four SBIR Phase 1 contracts in January 2013, including one to Busek Co., Inc. with funding provided by the Program Executive Office (PEO), Command, Control, Communications, Computers, & Intelligence (C4I). Space and Naval Warfare Systems Command (SPAWAR) exercised the Phase 1 option in July 2013.

In Phase 1 of the SBIR effort, Busek designed a radar altimeter payload to fit on the 3U bus from APL. Busek prototyped major enabling systems including sub-array panels, a radar frontend, a pulsed power system, and a compact deployable antenna. Busek determined that a 3U design was possible, but a 6U design would provide enhanced performance due to increased power available to the payload and more volume for a larger antenna¹³.

Reference Miniature Altimeter Payload (MAP) System Design

A reference MAP system was created as a reference baseline for this study. The design included a 6U satellite bus with a radar altimeter. The bus design included a laser retro-reflector and GPS receiver for precise orbit determination. Ground stations similar to the Mobile Cubesat Command and Control (MC3) were included.

The 6U “SUPERNOVA” bus, under development by Pumpkin, Inc for the fiscal year 2013 Rapid Innovation Fund program, was the basis for the space vehicle for the MAP reference design. The 6U SUPERNOVA bus is approximately 10 cm by 20 cm by 30 cm. The standard bus components include the solar panels, electrical power system, flight computer, attitude determination and control sub-system, UHF receiver, S-band transmitter, and an L1 GPS receiver. Those standard components take approximately 2.5U of volume, and allow for an extra 0.5U for payload in a 3U bus. The bus will provide up to 30 watt-hours of power to the payload on an average orbital period¹⁴.

The preliminary radar altimeter payload design from Busek was selected for the MAP reference design. 1U volume was assumed for the radar electronics. An antenna must be integrated into the spacecraft’s exterior, either on the bus structure or perhaps on the backside of the solar panels. Generally larger antennas have higher gain. The 6U bus will allow a larger antenna than the 3U bus originally considered, therefore it should get additional gain. Additional gain means

less power will be required for each radar pulse. Therefore, the pulse repetition frequency (PRF) could be increased, resulting in lower radar range error.

Precise orbit determination is a key factor in calculating sea surface height. Retro-reflectors were used on most previous altimetry missions to help achieve precise orbit determination. A modulated retro-reflector sub-system in development by SPAWAR Systems Center (SSC) Pacific was included in the MAP reference design to aid in orbit determination. The High-bandwidth Anti-jam LPI/LPD Optical Network (HALO-Net) project is developing an optical communication system, which will enable low size, weight, and power (SWaP), secure, Anti-Jam, LPI/LPD downlink and crosslink optical communications for a CubeSat-sized platform¹⁵. The intent of the HALO-Net project is to deliver assured communications in an RF-constrained environment, however the retro-reflector can also be used for precise orbit determination using laser ranging techniques, a key capability for radar altimetry systems.

Miniature Altimeter Payload Performance Prediction

Sea surface height is calculated as the difference between the satellite altitude and the range determined by the altimeter. Radar range error is the difference between the actual distance to an object and the distance the radar calculates, assuming no atmospheric distortions or other errors. Sea state bias accounts signal reflected preferentially from troughs versus crests of ocean waves, and thus the correction changes with wave height. Ionospheric refraction and dry troposphere effects are errors induced as the signal travels through the ionosphere and troposphere respectively. Wet troposphere effect is an error induced as the signal interacts with water vapor in the troposphere. Position or altitude error is the difference between the calculated location of the satellite and the true position.

The study team examined the overall performance of the reference design. Inputs from Busek, SSC Pacific’s HALO-Net team and NRL were taken into account. The minimum, expected (average), and maximum error for each component of the error budget were established by calculation where possible, with the remainder estimated using engineering judgment. An initial system error budget was created. The initial worst case, expected and best case errors were provided to NRL to enter in the ocean model.

The initial error budget was generated quickly because it takes a long time to run the ocean model. Later, the team revisited the error budget and adjusted some of the numbers based on the updated information and

additional analysis. Table 1 shows the revised miniature altimetry payload SSH error budget.

The Root Mean Squared (RMS) value for total error was computed using formula 1, where “x” is one component of the error, and “n” is the total number of error components. Individual errors already given in RMS were summed.

$$x_{RMS} = \sqrt{\frac{\sum_{n=1}^n x_n^2}{n}} \quad (1)$$

Table 1: Revised Sea Surface Height Error Budget

Item	Worst Case Error (cm)	Expected Error (cm)	Best Case Error (cm)
Radar Range Error	16	10	4
Sea state bias	4	3	2
Ionospheric refraction (RMS)	3.25	3.25	3.25
Dry Troposphere	3	2	1
Wet Troposphere / Water Vapor (RMS)	1.2	1.2	1.2
Position Error / Orbit altitude (laser ranging and GPS)	4	3	2
Total Error (RMS)	16.1	11.0	6.7

The system as-built should perform somewhere between the worst and best case for each error item. To estimate the likely performance of the system as a whole, a Monte-Carlo analysis was performed using the information in Table 1. A triangular distribution was assumed for each item. Ten thousand trials were performed.

Table 2 shows the cumulative distribution of the likely total nanosat error in centimeters. The data shows the likely worst case error was 15.6 cm and the likely best-case error was 7.3 cm. The data showed a likely error of 12.5 cm at the 80% cumulative distribution or confidence level. This means that for four of every five trials, the altimetry error was less than or equal to 12.5 cm. This is significantly below the initial estimate of 22.5 cm likely error.

Table 2: Cumulative Distribution of Miniature Altimetry Payload error

Cumulative Distribution	Error (cm)
10.00%	9.6
20.00%	10.2

30.00%	10.6
40.00%	11.0
50.00%	11.3
60.00%	11.7
70.00%	12.0
80.00%	12.5
90.00%	13.2
100.00%	15.5

Model-Based Propagation Correction Errors

The corrections for total precipitable water content and total electron count are typically based on onboard measurements by microwave radiometer and dual frequency altimeters. These systems do not exist on the nanosat altimeter system. Thus, the corrections must be derived from model forecast sources. Such sources have been used for the Geosat geodetic mission, the Geosat-Exact Repeat Mission, portions of the GFO mission and others. Error estimates in the model-based corrections are derived from the Jason-2 geophysical data records (GDRs). The GDRs provide both the satellite observed values and model-based corrections. A total of 60 days is used in the analysis. The water vapor correction is based on the European Center for Medium-range Weather Forecasting (ECMWF), and the ionosphere correction is based on the Global Ionospheric Maps (GIM) constructed at the Jet Propulsion Laboratory (JPL). The scatter plot results are shown Figure 1 and Figure 2 below. The difference between model-based correction and the value derived from the satellite sensors is 1.2 cm for the total precipitable water vapor and 3.2 cm for the total electron count. When it was compared to the error levels simulated for the nanosat altimeter, these are small contributions. For example, the total RMS for the sensor noise level of 10.5 cm, 1.2 cm water vapor and 3.2 cm electron count results in a total RMS error of 11.0 cm. The sensor error is the dominant source for the nanosat altimeter system. Thus, noise models for the water vapor and electron count are not constructed and added to the SSH sampled from the nature run.

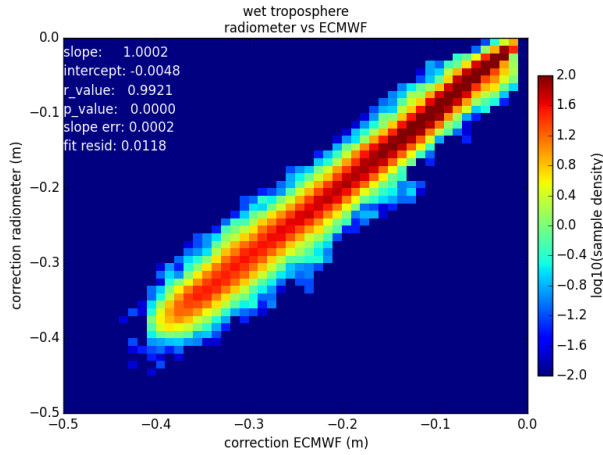


Figure 1: Wet Troposphere Radiometer versus ECMWF model

The correction for total precipitable water vapor observed by the microwave radiometer on Jason-2 is compared to the value estimated by the ECMWF atmospheric forecast. The plot shows the number of occurrences in each bin. The color bar indicates the \log_{10} of the value. The RMS difference is 1.2 cm. Figure 1 shows that the ECMWF forecast can be used in place of a radiometer on board a nanosat at the cost of 1.2 cm error.

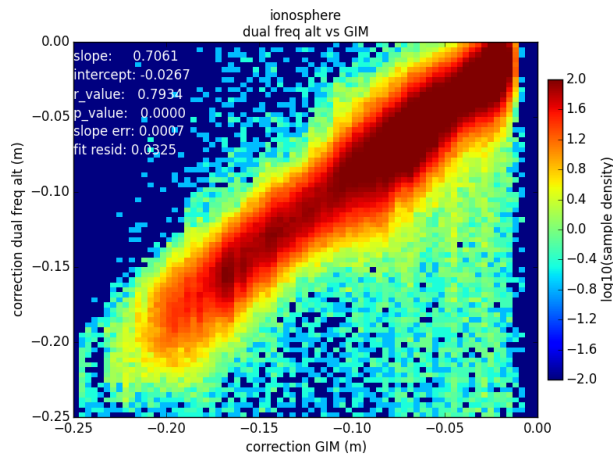


Figure 2: Ionosphere Dual Frequency Altimeter versus GIM model

The correction for total electron content observed by the dual frequency altimeter on Jason-2 is compared to the value estimated by the GIM ionospheric model forecast. The plot shows the number of occurrences in each bin. The color bar indicates the \log_{10} of the value. The RMS difference is 3.2 cm. Figure 2 shows that the GIM model can be used in place of a dual frequency altimeter onboard a nanosat at the cost of 3.2 cm error.

OCEAN MODEL RESULTS

The first evaluation is the ability to reconstruct Sea Surface Height Anomaly (SSHA) directly from the simulated data by a simple interpolation. The interpolation is constructed at 00Z for each day of the experiment. The anomaly correlation to the nature run sea surface height is computed each day. For comparison, tidal variability at the 8 most significant frequencies is estimated and removed from the model solution. At the same time, the annual and semi-annual frequencies are estimated and removed. SSHA values in water depths greater than 1000 m are used in the correlation analysis, and values in shallower water depths are not used. The SSHA in shallow water is driven by transient winds and does not reflect the interior temperature and salinity variations that are the primary drivers of acoustic propagation variation. Figure 3 shows the time series of daily correlation values for the Jason-only experiment. This provides the reference for comparison to other experiments with different nanosat constellations and error levels. The correlations of the constellations of 2, 4 and 6 nanosats for low, medium and high error levels are computed relative to the nature run in a manner identical used to compute the results in Figure 3. From the correlations for 2, 4, and 6 nanosats, average correlations over the 1.5 years are computed. The mean values and the fraction of the 1.5 years during which the correlation is greater than 0.6 are provided in the plots as well.

Figure 3 shows the SSHA correlation between the interpolated Jason data and the SSHA of the nature run. Tidal, annual and semi-annual variability have been removed from both data sets, and correlation is computed using data only in water depths greater than 1000 m.

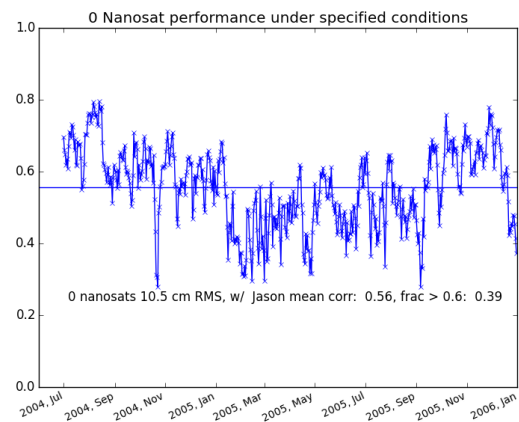


Figure 3: Jason-only SSHA Correlation

Figure 4 show the SSHA correlation between the interpolated data using 2 nanosat satellites and the

SSHA of the nature run. Blue indicates 10.5 cm RMS with Jason, red indicates 22.5 cm RMS with Jason, black indicates 22.5 cm RMS without Jason, and green indicates 40.5 cm RMS with Jason. Tidal, annual and semi-annual variability have been removed from both data sets, and correlation is computed using data only in water depths greater than 1000 m. The low, medium and high error ranges are shown together.

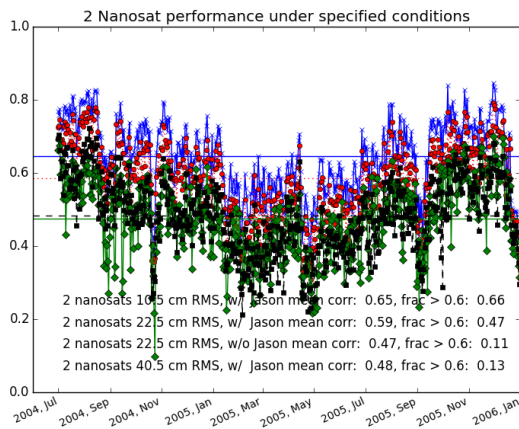


Figure 4: Two Nanosats SSHA Correlation

The summary of the results is provided in Table 3. The summary is consistent with expectations in that higher nanosat error levels result in poorer performance relative to the Jason-only data set. Increased numbers of sensors in the constellation improves performance relative to Jason-only.

The summary of interpolated simulated SSHA under the different nanosat constellations and error levels are color-coded relative to the interpolation using Jason-only. Green indicates the constellation and error levels are better than Jason only, yellow indicates similar performance, and red indicates worse performance.

Table 3: Sea Surface Height Anomaly Correlation

Error Level	2 Nanosats	4 Nanosats	6 Nanosats
10.5 cm with Jason	0.65	0.71	0.73
22.5 cm with Jason	0.59	0.65	0.68
22.5 cm w/o Jason	0.47	0.57	0.62
40.5 cm with Jason	0.48	0.54	0.56

The study also considered a number of statistics including: Mixed Layer Depth, Steric Height, Frontal Forcing and Surface Divergence. Those results are omitted for minimize the length of this paper.

Nanosat errors as high as 40.5 cm RMS do not result in consistent improvements beyond the Jason-only case, and in many cases result in worse performance. At nanosat error levels of 20.5 cm RMS, most metrics show improvement over Jason-only results if the

nanosat constellation contains 4 or 6 separate sensors. At nanosat error levels of 10.5 cm, all the metrics indicate performance beyond Jason-only in all constellations from 2 to 6 nanosats.

COST-EFFECTIVENESS ANALYSIS

“The U.S. Office of Management and Budget (OMB) defines cost-effectiveness as “a systematic quantitative method for comparing the costs of alternative means of achieving the same stream of benefits or a given objective.” OMB further states that “cost-effectiveness analysis is appropriate whenever it is unnecessary or impractical to consider the dollar value of the benefits provided by the alternatives under consideration¹⁶”. It is often difficult to assign a dollar value to the outcome of military operations; therefore cost-effectiveness analysis was the most appropriate method to compare nano-satellites with traditional satellites.”¹¹

Methodology

The cost-effectiveness analysis follows the process described in Mroczek’s thesis “determining the cost-effectiveness of nano-satellites”¹¹. The radar altimetry analysis in the thesis has been significantly updated as part of this study. The objective hierarchy has been modified to focus on the outcomes of the ocean model instead of the accuracy of the radar altimeter. Input on the measures of effectiveness, threshold/objective values and the importance of each measure has been updated based on subject matter expert feedback. A Jason-3 only mission is compared to Jason-3 augmented by 2, 4, and 6 nanosat constellations.

Cost-Effectiveness Analysis Results

The cost and effectiveness for Jason-3 only, and then Jason-3 plus various combinations of nanosats at different accuracy levels were calculated. Finally the increase in cost and effectiveness were calculated, and are shown in Table 4. For example, a system with four satellites at 22.5 cm accuracy provides an 80% effectiveness increase for a 37% cost increase.

Table 4: System Costs and Effectiveness Increases

System / Option	% Cost Increase	% Effectiveness Increase
Jason-3 Only	0	0
2 Nanosats 10.5 cm	22%	73%
2 Nanosats 22.5 cm	22%	51%
2 Nanosats 40.5 cm	22%	15%
4 Nanosats 10.5 cm	37%	109%
4 Nanosats 22.5 cm	37%	80%
4 Nanosats 40.5 cm	37%	53%
6 Nanosats 10.5 cm	52%	113%

6 Nanosats 22.5 cm	52%	88%
6 Nanosats 40.5 cm	52%	57%

CONCLUSIONS

The study shows the reference design for the MAP should be less than 16.1 cm RMS error and will be only 12.5 cm RMS error at the 80% confidence level. This is lower than the initial 22.5 cm RMS “medium error” case used to evaluate the output of the ocean model. At 22.5 cm RMS error, two nanosats would provide a 51% increase in effectiveness for a cost increase of 22%, while four nanosats would provide an 80% increase in effectiveness for a cost increase of 37%.

A nanosat demonstration mission could verify the ability to build a radar altimeter mission that meets the performance studied. The cost to develop, launch and demonstrate a MAP similar to the reference design is relatively low to demonstrate a space-based capability.

Acknowledgments

The authors would like to acknowledge the Oceanographer of the Navy for providing funds for the study underlying this paper.

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