ABSTRACT
ABYSS (Altimetric Bathymetry from Surface Slopes) will map the ocean floor 100 times faster and cheaper than ships can, by using a state-of-the-art delay-Doppler radar altimeter on board the International Space Station. The ISS orbit is nearly ideal for this application, and the advanced altimeter is tolerant of platform motions. The altimeter can see subtle tilts in the ocean surface caused by seafloor topography. Bathymetric depth and roughness control the circulation and mixing of heat through the ocean, which in turn controls climate. Only 0.1% of the deep ocean has been mapped in enough detail so far. ABYSS will complete this survey over 80% of the world’s oceans.

INTRODUCTION
The ABYSS (Altimetric Bathymetry from Surface Slopes) mission is simple, focused, and cost-effective, because it has one goal – bathymetry – that requires one measurement – sea surface slope – by one instrument – a precision radar altimeter. Sea floor topography steers ocean currents and increases ocean mixing (Fig. 1), and so bathymetry is a necessary prerequisite in the study of the ocean’s role in, and response to, climate and climate change. There are critical gaps in the understanding of these processes because only 0.1% of the ocean floor has been mapped at process-critical spatial scales. ABYSS will obtain the necessary data with a one-time measurement, opening a new window on global change processes. The International Space Station (ISS) orbit is optimal for this purpose: it will furnish nearly isotropic resolution while covering more than 80% of the global ocean area. Motions of the ISS (apart from orbit boosts and shuttle docking) do not pose a problem for ABYSS.

We focus the overall goal – bathymetry – into three specific objectives that address three NASA Earth Science research questions on ocean circulation, sea level, and surface change. These objectives drive the mission design. Two other objectives – continental margin structure, and ocean wind speed and wave height – can also be addressed with the same design. The same measurement – sea surface slope – reveals sea floor topography over the deep ocean and sedimentary basin structure over continental margins. The same instrument which measures sea surface slope – the altimeter – also measures wind speed and wave height.

OBJECTIVES

Objective 1

OBJECTIVE #1 OF ABYSS IS TO FURNISH BATHYMETRY TO 6 KM HALF-WAVELENGTHS FOR USE IN OCEAN CIRCULATION STUDIES. The global ocean circulation must be correctly characterized and modeled before one can accurately predict climate-driven changes. Bathymetry steers ocean currents, constrains the exchange of deep water between ocean basins, and influences the formation and dissipation of eddies. Float, drifter, and satellite observations of ocean flow, salinity, and sea ice all require detailed bathymetry for interpretation. Ocean general circulation models (OGCMs) are now able to ingest high-resolution bathymetry, significantly improving their flow pattern analyses. OGCMs produce plausible circulation only when they are run at resolutions of 0.1° or less, fully resolving mesoscale length scales, which range from 10 km at 60° latitude to 30 km at
2. The accuracy of OGCMs is now limited by the lack of bathymetry at these scales, and this lack will become more acute in coming years, as the ability of computers to simulate ocean physics is rapidly evolving.

Objective 2

Objective #2 of ABYSS is to characterize the spatial variations in the seafloor roughness spectrum that control ocean mixing. Global sea level depends on both ice flux and thermal expansion, and will require an understanding of how the ocean absorbs and distributes heat. Seafloor roughness is a major factor that controls mixing of heat and salt through the ocean. As well-organized flow encounters rough bottom it becomes turbulent; horizontal motions are converted into vertically propagating waves, and kinetic energy is put to work mixing the ocean. Bottom roughness variations change surface eddy kinetic energy dissipation by a factor of three, and vertical diffusivities by as much as a factor of ten. Mixing rates increase where tides encounter rough bottom, and 25–30% of tidal energy is dissipated in the deep ocean. Tides may be the dominant source of energy for mixing the deep ocean, and may modulate climate on decadal to millennial time scales. Mixing process studies require the spectrum of seafloor topography in the direction of flow and over length scales from 100 m to 100 km. These spectra (Fig. 2) have a characteristic fractal decay at full-wavelengths shorter than 20–40 km. Other spectral shape parameters depend on local roughness and orientation because abyssal hills have aspect ratios of 2 to 6. By resolving topography isotropically to 12 km full-wavelength, ABYSS will characterize the overall spectrum shape in all directions, placing global ocean mixing and energy dissipation studies on a realistic foundation.

Objective 3

Objective #3 of ABYSS is to resolve the critical details of seafloor spreading and micro-plate tectonics. Sea floor spreading has resurfaced 70% of the Earth in the last 2% of Earth history, operating in two characteristic modes. One mode generates rough seafloor at a ridge with an axial valley. The other mode creates smooth seafloor at a ridge with an axial high. These two modes are very different.

Figure 1. Radar altimetry maps sea-floor roughness. Conventional bathymetry (top) from ship soundings (dots) fails to characterize seafloor roughness. The US Navy’s Geosat and ESA’s ERS-1 revealed some large-scale roughness transitions (middle). NASA’s ABYSS mission for the first time will image the smaller scales of roughness that are critical controls on ocean mixing (bottom), currents, and climate.
ent; rms amplitudes and abyssal hill lengths and widths vary by a factor of 5 (Fig. 2). Spreading rate, mantle thermal structure and magma supply may be roughness controlling factors, but abrupt transitions occur and the process controls are not yet understood because the ocean floor is not mapped at high enough resolution. Noise levels in existing data are so high that only a few details of abyssal hill fabric can be seen, and then only when roughness amplitude is large. Furthermore, the resolution of existing data is strongly anisotropic and they show the widely spaced E-W fracture zones of first-order plate tectonics (Fig. 1), but not the fine scale roughness produced by micro-plate tectonics, such as ridge axis discontinuities (e.g., the Overlapping Spreading Center, OSC, in Fig. 2). ABYSS will obtain nearly isotropic resolution of structures down to 6 km half-wavelength, permitting the study of micro-plate tectonics and the roughness controlling mechanism, and will obtain these data nearly globally, in contrast to the NSF RIDGE program which maps only a few sites on ridge axes. ABYSS data will characterize the geologic history of basin topography and roughness – important controls on paleo-climate that set the context for climate change debate.

**Space-based measurement**

Depth is measured in modern times by echo-sounders on ships, but most of those data are sparsely and irregularly distributed, with gaps of 100s of km between surveys. In many areas the majority of data are unreliable, having been collected by archaic means early in the last century. Typically, those data have depth errors exceeding 100 m. Although the acoustic swath mapping systems available for the last two decades allow ships to image bathymetry in 100 m pixels with errors of a few meters, less than 0.1% of the ocean floor has been so mapped. The data shown in Fig. 2 are exceptional: these are the only two deep-water areas on Earth where there are enough data to make this illustration. A ship-based survey of the oceans would take hundreds of ship-years and cost billions of dollars. ABYSS will furnish the crucial process-revealing data in six years at a cost of a few tens of millions of dollars. Sea floor topography is essentially constant on human time scales, so a space-based measurement needs to be made only once.

**Figure 2.** Examples of seafloor topography and ABYSS spectral resolution improvement. (Each image is 200 km on each side.)
Measurement requirements

The physical principle behind ABYSS is simple. Topography on an interface between two volumes of differing mass density produces gravity anomalies, and these are manifest in ocean surface slopes measurable from space with a precision radar altimeter. In the deep ocean, sediments are thin and oceanic crust is internally flat-layered, and so topography on the ocean floor is the cause of surface slopes. Conversely, at continental margins the seafloor is nearly flat, sediments are thick, and there are sub-seafloor sedimentary basins; here, displacements of the interface between sedimentary and crystalline rocks give rise to slopes in the same way. The correlation between slope and existing depth soundings readily distinguishes the two environments. ABYSS will reveal ocean floor topography and also continental margin sedimentary basin structure with the same measurement.

These are the key ideas behind the ABYSS mission:

• The necessary signals are band-limited (12 km to 400 km full-wavelength); error sources in only this band are of concern; longer wavelength accuracy/stability is irrelevant, simplifying instrument and mission design.
• Within this band, high precision is required (1 microradian (µrad) of slope, or 6 mm height change per 6 km along-track); the altimeter must have better precision than flown before.
• The orbit should not repeat for ~1.2 years, to yield a ground track spacing of 6 km, and should have an inclination near 50° or 125°, to resolve north and east slopes nearly equally.

Six years of data collected by a delay-Doppler altimeter on board the International Space Station (ISS) meets all the science objectives, with reserve.

The science signal is band-limited

Seafloor topographic variations must fall within a certain range of spatial extent – or band of wavelengths – to be observable by their associated surface slope signals. Short-wavelength signal amplitudes are damped by “upward continuation” and the resolution limit depends on signal strength and measurement noise levels. For seafloor topography a practical lower bound is 12 km full-wavelength. Topography produces little slope at (full) wavelengths longer than ~400 km due to “isostatic compensation”. The band of wavelengths between ~400 km and ~160 km is sensitive to the compensation mechanism, while wavelengths shorter than 160 km are largely unaffected by isostasy and can be directly related to seafloor topography. When conventional soundings are combined with altimetry, the soundings furnish the longer wavelengths and the altimetry fills in the scales shorter than 160 km.

Slopes reveal the signal

Sea surface slopes reveal gravity anomalies because the primary component of sea surface height is geoid height, the elevation of an equipotential of the gravity anomaly field. The geoid height at a point is the integral of anomalies over the entire earth, and one must differentiate the geoid to reveal local anomalies. The horizontal derivatives (slopes) of the geoid indicate anomalies in the direction of gravity called “deflections of the vertical”; their north and east components can be combined to recover gravity anomalies because the three components of the gravity vector are coupled through Laplace’s equation. A gravity anomaly of 1 mGal (10^-8 m s^-2, or about 10^-6 of total gravity) is related to a geoid slope of 1 µrad (10^-6 radian, or 1 mm height change per km). ABYSS will measure slopes to the order of 1 µrad (down to 12 km) to adequately resolve sea floor topography.

Inclination and azimuthal anisotropy

The direction of ocean flows and of elongation of abyssal hills varies from place to place, and so ABYSS is designed to obtain high
resolution equally at all azimuths. This requires that errors propagate nearly equally into any two orthogonal components of slope, such as north and east. This cannot be achieved by combining height profiles along ground tracks into a height map and then differentiating the map, since that approach would carry long-wavelength along-track height errors into short-wavelength across-track slope errors. Instead, one should obtain north and east slope components by vector projection of along-track slopes from ascending and descending ground tracks. This method is the least error-prone, but the relative amplitude of north and east errors depends on the latitude-dependent angle of track intersection.

Existing altimeter data along densely spaced (~6 km) ground tracks were obtained by the Geosat and ERS-1 geodetic missions, and these data suffer a severe anisotropy in slope error (Fig. 4a): at low latitudes the error in the E-W component of slope is 3 times larger than the error in the N-S component. This is because the orbital inclinations of these satellites carried them to high latitudes, giving their ground tracks a nearly N-S direction and small crossing angle at low latitudes. ABYSS will use a more moderate inclination in order to measure the north and east components with nearly equal error (Fig. 4a). While this inclination will not cover all latitudes, it still covers more than 80% of the ocean (Fig. 4b) because most of the ocean area lies at lower latitudes. ABYSS will use a more moderate inclination in order to measure the north and east components with nearly equal error (Fig. 4a). While this inclination will not cover all latitudes, it still covers more than 80% of the ocean (Fig. 4b) because most of the ocean area lies at lower latitudes. If one is free to choose the orbital inclination then there is a trade-off between maximizing the ocean area covered, and minimizing the anisotropy averaged through the area covered. It turns out that the ISS inclination (51.6°) almost exactly optimizes this trade-off (Fig. 4c). ABYSS on the ISS will improve the precision in east slopes by a factor of 7 and north slopes by a factor of 3 over existing data.

INSTRUMENTATION

Science requirements for bathymetry from space dictate both a preferred orbit, and a preferred instrument. The International Space Station (ISS) is a cost-effective candidate as a host platform that satisfies the orbital constraints, and the Delay-Doppler Altimeter (DDA) is the only known approach that can satisfy the measurement constraints set by the science requirements.
quires that these large angles do have to be compensated. Unlike other altimeters, the DDA is inherently capable of measuring these orientation errors, and offsetting them. The ABYSS design introduced in this section is necessary and sufficient to produce the required measurements under the constraints imposed by the ISS.

**The DDA altimeter: an introduction**

The ABYSS science instrument is a Ku-band, delay-Doppler, pulse-limited radar altimeter. The primary measurement of a pulse-limited altimeter is the minimum distance (range) between the radar and the ocean’s surface. This measurement is inherently robust because it does not require precise attitude knowledge of the instrument. However, active pointing is required to keep the radar aimed at nadir within the tolerance set by the antenna beamwidths. This requirement is met by closed-loop control of a gimballed antenna platform. Pitch and roll angles away from nadir are measured by separate means. Antenna pitch is proportional to the signal’s average Doppler frequency. Antenna roll is proportional to the phase difference between the signals received at two antennas separated in the cross-track plane. These indications of pitch and roll mispointing are applied as steering commands to the gimballed antenna platform, thus maintaining accurate nadir pointing in spite of ISS angular motions. The nominal ISS attitude information is provided to the instrument to facilitate nadir reacquisition after passing over land.

**Selection criteria for the DDA**

The DDA has a smaller along-track footprint than a conventional radar altimeter, and also has better measurement precision. A delay-Doppler altimeter in the ISS orbit provides significantly better precision than a conventional radar altimeter, and the improvement increases with significant wave height (Fig. 5). This is important for ABYSS, as wave height was the major source of noise in Geosat surface slope estimates. Small footprint and better precision are both necessary to meet science requirements. Delay-Doppler signal processing supports near-shore range-gate tracking much better than is possible with any conventional altimeter. Near-shore performance is required. These measurement advantages are in addition to the unique capability of the DDA to measure and compensate for the angular pointing variations imposed by the ISS. Ku-band is the preferred radar wavelength (2.2 cm) because it has been proven to support radar bathymetry through the Geosat and ERS-1 missions.

**High-level science data products**

Algorithms for the production of bathymetry proceed from the GDRs via the intermediate step of producing gravity fields. The gravity fields incorporate model field data; ABYSS will use GRACE or other state of the art models.

**Innovative aspects**

The ABYSS altimeter design exploits Doppler and interferometric phase comparison to maintain closed-loop nadir pointing of the radar. Without active pointing, the altimeter would have to have antenna beamwidths in roll and pitch sufficiently large to embrace the expected ISS attitude variations. This would imply an antenna area less than 1/10 of our design, which then would require 100 times more power to achieve the same performance. That would not be feasible. Electronic beam steering could be used, but the resulting antennas and their control electronics would be much more complex, costly, and risky than the current design. Again, that would not be feasible.

The smaller footprint and measurement variance that characterize ABYSS are innovative and proven features unique to the delay-Doppler paradigm.

Both the concept and the instrument of ABYSS constitute a highly innovative, low risk, high science-value mission.
**ABYSS radar altimeter**

The ABYSS radar altimeter is a descendent of past instruments such as the JHU/APL-built NASA altimeter on the TOPEX/Poseidon satellite. ABYSS will be simpler than TOPEX, in that only one frequency is required. Also, there is no need for an on-board water-vapor radiometer, and the lower power requirement can be met with a solid-state device rather than a travelling wave tube. To support delay-Doppler signal processing, the ABYSS altimeter will maintain a constant phase reference between successive radar pulses within each burst. Among other advantages, Doppler analysis of the coherent data generates the gimbal’s reference signal for the antenna pitch control. A second receive channel and antenna are arranged as a cross-track interferometer to generate the gimbal’s reference signal for the roll control.

The altimeter will transmit from one antenna, and receive on both antennas. Only one receiver is required to serve the science requirements. The basic design of the instrument is the same as that used by the D2P altimeter, developed under NASA Instrument Incubator funding. ABYSS also has extensive heritage to previous spaceborne altimeters such as TOPEX and Geosat. The transmitted waveform is a linear, frequency-modulated pulse. The ABYSS altimeter will transmit a group of contiguous pulses within each burst. This pulse burst approach is well-suited to the rather large ranges encountered from a space-based platform, and also is well-suited to the subsequent coherent processing steps of the delay-Doppler algorithm.

A gate array in the transmitter and frequency synthesis section provides all of the critical timing functions such as the transmission trigger, synchronization, digitization, etc. Processing of the digitized data will be performed by a combination of special purpose hardware (the waveform processor) and software in a general-purpose computer, as is the case for past altimeters such as TOPEX. The only real-time demand on the computer is incoherent integration of waveform (at an average rate of 6.2 million samples per second). Height and attenuation tracking will be performed at the 25 Hz rate. Gimbal control will be at a rate on the order of once per minute. These processing requirements with the addition of general housekeeping functions, can be met with a wide variety of space-wide variety of space-qualified processors such as the Power PC 603 which has flight heritage, or the 750 which is planned for several missions in low-radiation environments such as the ISS.

A parametric description of the ABYSS radar altimeter is contained in Table 1. The single-pulse noise equivalent sigma-0 for this system is 15.1 dB. This provides 5 dB reserve relative to the science requirements.

The altimeter will be laid out as subsystem elements on a chassis baseplate attached to an EXPRESS pallet adapter, as illustrated in Fig. 6. The baseplate will be thermally isolated from the adapter. The 134 W of heat from ABYSS will be radiated into free space.

| Table 1. Radar Altimeter Parameters |
|-----------------|-----------------|
| Parameter       | Value           |
| Frequency       | 13.5 GHz, Ku-band |
| Pulse length    | 2.097 ms        |
| Waveform        | 32 linear fm sweeps (per burst) |
| Bandwidth       | 320 MHz         |
| Pulse rate      | 188 Hz          |
| Pulse power     | 10 watts        |
| Antennas (two)  | Patch arrays 0.36 x 0.97 m (each) |
| Antenna pointing| Nadir, 2-axis gimbal, ∀ 10° |
| Along-track pixel| 285 m (after processing) |
| Across-track pixel| 2 km (@ 1 m wave height) |
| Sigma-0 (nominal)| 10 dB           |
| Passive losses  | 5 dB            |
| Measurement rate| 25 Hz           |
| Single pulse SNR| 15.1 dB (nominal, 400 km) |
| Altitudes       | 350 km – 470 km |
| Baseline Mission| Fully redundant (active), 6 years |
| Minimum Mission | No redundancy, 3 years |
**Science data handling**

The science data rate is budgeted at 45 kbps. Of this, ~9 kbps is a contingency allowance above the 36.1 kbps science data. Science data include three types of products generated on-board. The primary outputs are height waveforms (25.9 kbps, delivered at 25.3 Hz, 64 points each waveform, 16 bits each point). These products are similar to their TOPEX and Geosat counterparts. The secondary products are scattering function profiles, as distributions in Doppler frequency (8.2 kbps, comprising sets of 32 Doppler-registered integrated waveforms at 0.25 Hz, 64 points each waveform, 16 bits each point). The tertiary products are integrated cross-channel waveforms (2 kbps, at 0.25 Hz, 256 points each waveform, 32 bits each point). Doppler profiles and cross-channel waveforms have valuable information on antenna pointing, wind speed and wave height in along- and across-track directions. Conventional radar altimeters are not able to provide this information.

**Reserves and margins**

In addition to the total power and mass reserves in the design, the ABYSS altimeter includes performance contingencies in transmitted power, burst averaging, and pulse timing. In general, an altimeter’s height measurement error is limited by two potential degradations: speckle (or multiplicative noise), and additive noise. The impact of additive noise can be mitigated by increasing transmitter power, and by reducing system losses. The ABYSS altimeter design is based on providing enough power in the transmitted pulse to eliminate additive noise as a concern for the science value of the data. Simulations have shown that a single-pulse SNR of 10 dB or greater results in the receiver noise having a small impact on system performance\textsuperscript{53}. The ABYSS altimeter design, including 5 dB of unspecified passive losses within the transmission lines and connectors, provides 15 dB of SNR, which includes a 5dB contingency.

*Speckle* is the noise-like amplitude variation imposed on radar reflections from random surfaces. Speckle can be reduced only through incoherent (burst-to-burst) averaging of many waveforms. The ABYSS design, thanks to the delay-Doppler paradigm, incorporates extensive incoherent averaging, sufficient to meet the measurement requirements with contingency. ABYSS will average 231 bursts within each measurement area (pixel), and generates averaged waveforms at a rate of 25 Hz, for a total of 5775 bursts averaged per second per pixel. Simulations have shown that a delay-Doppler altimeter that averages 5000 bursts per second of final waveforms will achieve height precision of 1 cm for a 4-meter significant wave height\textsuperscript{53}. This provides a reserve against science requirements of approximately 25%.

The timing of the transmitted bursts provides contingency against platform altitude variations. The minimum operational altitude is determined by the burst length of 2.097 ms. This limit corresponds to an altitude of 315 km which is 35 km less than the expected ISS minimum of 350 km. The maximum operational altitude is determined by the burst frequency of 188 Hz as well as the burst length. This limit is 483 km, which is 13 km greater than the expected ISS maximum of 470 km.

The fundamental compatibility between ABYSS requirements and ISS requirements and characteristics has been established through reference to extensive ISS documentation, and verified by discussions with ISS engineers and interface personnel. ABYSS meets the physical constraints expected of the completed ISS\textsuperscript{56} with considerable margin, as detailed in Table 2. Of these parameters, roll rate deserves comment, having a margin of 50% in contrast to the
50% in contrast to the much larger headroom on the other parameters.

The roll rate requirement is driven by science, which stipulates that ABYSS is to measure surface slopes over spatial scales of 12km-400km from a pallet on the transverse truss. The pallet site is approximately 40m from the center of ISS mass. Because of this long lever arm, an unknown ISS roll rate of 0.003 deg/sec would translate into a surface slope uncertainty of 0.5 microradian. This is acceptable. The roll rate knowledge uncertainty (0.002 deg/sec) predicted for the ISS fits comfortably within that constraint.

**Heritage**

The ABYSS altimeter enjoys extensive heritage from previous spaceborne and airborne instruments. The pulse modulation and bandwidth are the same as those of Geosat and TOPEX, both designed and built by JHU/APL. The contiguous-pulse burst mode is an innovation that introduces rather greater robustness than the TOPEX interleaved-pulse design. Radar pulse and timing parameters are implemented in a programmable gate array device, whose functions have been demonstrated in the D2P Instrument Incubator radar, and whose hardware has extensive flight heritage. For example, the D2P antenna pair (see Fig. 7) is in effect a one-half scale prototype of the patch array antenna planned for ABYSS.

Solid-state power amplifiers (SSPA) have performed well in previous altimeters such as Poseidon and GFO (7W, Ku-band), and have flight heritage in JHU/APL spacecraft such as NEAR (X-band). As proven in the D2P altimeter, the delay-Doppler altimeter requires less transmit power than a conventional altimeter. The ABYSS solid-state design is conservative, and low-risk.

The receiver is designed around the “full deramp” technique in which the first down-conversion removes the frequency sweep of the received pulse. This technique is highly advantageous. It reduces the bandwidth of the receiver output by a factor of about one hundred, and simplifies subsequent digitization and signal processing requirements. The full deramp technique was first introduced into radar altimetry with JHU/APL’s Seasat altimeter in 1978, and has become the standard for all high-performance space-based radar altimeters.

**Risks**

There is little risk that the mission will fail to meet the science goal because of theory, algorithm or instrument problems. The biggest risk factor is mission delay caused by ISS EXPRESS program slippage. Bathymetry from ABYSS is needed now, as lack of bathymetry has become a limiting factor in the accuracy of climate change forecasts from OGCMs; this need will only be more acute by the time ABYSS is ready to fly. The science can be done from any spacecraft of opportunity with a suitable orbit (non-repeat, inclination near 50° or 125°), and the ABYSS mission should be moved from the ISS to another platform if ISS suffers delays and another opportunity arises.
CONCLUSIONS

ABYSS is a focused mission with one primary goal: bathymetry, in three specific objectives (seafloor spreading scales, OGCM boundary conditions, roughness spectra for mixing) matched to three NASA global change process research questions. The one goal requires one measurement: sea surface slope. All the science objectives require the same slope attributes (high-precision, limited band, isotropic error projection). This drives the design of the sensor and the mission. Only one sensor is required. Since the same sensor and mission also deliver valuable data on the structure of continental margins and the wind and wave environment of the oceans, these have been included as secondary objectives. They add science return and bring in investments from partner agencies and industries without altering the mission design or primary goal.

The science requirements of ABYSS are supported almost optimally by the inclination and random repeat pattern of the International Space Station. The attitude variations expected at the instrument pallet site on the Space Station are compensated by the advanced DDA radar altimeter planned for this application.

ABYSS is being proposed through the NASA ESSP opportunity.

REFERENCES


11 American Institute of Aeronautics and Astronautics