SSC99-VII-7

WITTEX: A Constellation of Three Small Satellite Radar Altimeters

R. Keith Raney, Glen H. Fountain, Robert E. Gold, Ark L. Lew, and David L. Porter

The Johns Hopkins University
Applied Physics Laboratory
11100 Johns Hopkins Road
Laurel, MD 20723-6099
keith.raney@jhuapl.edu; glen.fountain@jhuapl.edu; robert.gold@jhuapl.edu;
ark.lew@jhuapl.edu; david.porter@jhuapl.edu

Abstract. WITTEX, named in honor of E. Witte, who in 1878 first discovered the geostrophic current equation, is an acronym for Water Inclination Topography and Technology Experiment. WITTEX consists of three co-planar small satellite radar altimeters launched on the same vehicle into a GEOSAT-class orbit. The proposed satellite constellation would support measurement for the first time of both orthogonal components of the ocean's surface slope, rather than the single component seen by conventional instruments. The satellites are spaced by several kilometers along their orbit; Earth rotation causes their sub-satellite tracks to be laterally separated. Track separation can be readily adjusted by selection and autonomous control of inter-satellite spacing. If the satellite spacing were about 900 km, then the sub-satellite orbit tracks would fall approximately uniformly 53 km apart at the equator. This spacing is nearly optimal for observing oceanic eddy fields and surface energy transport. The enabling conceptual innovation is the delay-Doppler radar altimeter (DDA). Studies have shown that this technique yields more precise measurements than a conventional radar altimeter, yet it requires much less transmitted power. The notional instrument has two frequencies and an onboard water vapor radiometer, similar to TOPEX. The DDA approach, combined with recent advances in spacecraft technology, leads to substantial miniaturization; the goal is to use Pegasus as the launch vehicle. The enabling technologies include the Integrated Electronics Module (IEM), chip-on-board (COB), and the Command and Data Handling In-Your-Palm (CDHIYP), all developed at The Johns Hopkins University Applied Physics Laboratory (JHU/APL). The WITTEX concept is a flexible, capable, unique, and cost-effective approach that will significantly advance the state of the art in both technical and scientific arenas.

I. Introduction

The Johns Hopkins University Applied Physics Laboratory (JHU/APL) has both dominated and led in satellite radar altimetry from the outset in the early 1970s. JHU/APL led NASA's GEOS satellite series, which culminated in the first radar altimetric satellite, GEOS-3. The expertise developed on GEOS-3 led directly to the radar altimeter for NASA's SEASAT mission (1978), an altimeter that introduced an ingenious signal modulation technique used by all subsequent radar altimeters. When the SEASAT spacecraft power system failed after ~99 days in orbit, JHU/APL recognized the Navy's then unmet geodesy requirements and recommended the development of a dedicated radar altimetry mission. Subsequently the Navy sponsored the development of GEOSAT.[1] Advances in the technology from GEOS-3 through GEOSAT led to the development of the TOPEX[2] radar altimeter, whose data are used extensively by the geophysical community. Its ~3-cm height accuracy sets the standard for such measurements. The surface pattern of TOPEX tracks is shown in Figure 1.

Certain limitations of conventional radar altimeters led to the development at JHU/APL of the delay-Doppler radar altimeter (DDA) concept.[3] This new technique reduces onboard mass and power requirements and also improves measurement precision. The DDA concept, coupled with recent

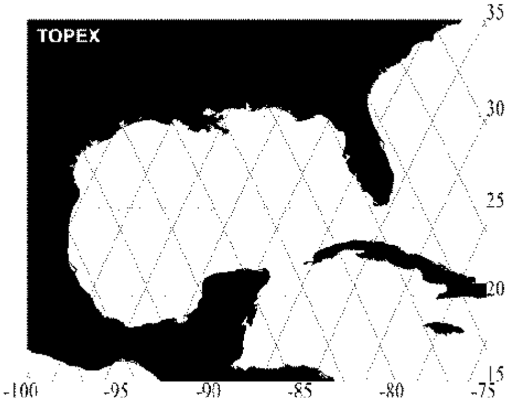

Figure 1. Example of one full cycle of coverage (~10 days) by the TOPEX/Poseidon radar altimeter. Equatorial track spacing for TOPEX is about 315 km.

advances in technology and miniaturization, makes a small satellite radar altimeter feasible for the first time.

II. Advanced Altimetry

The possibility of building small satellite radar altimeters is coming at an opportune time. The geophysical community is calling for sea-surface height measurements that go beyond the capabilities of present systems.[4] The new requirements include more complete coverage of the surface by measurement tracks and a means to measure cross-track surface slope. Conventional radar altimeters can derive precise surface height measurements only along the nadir track. Off-track altimetry from a single instrument would induce new and unacceptable sources of measurement error.

Single-satellite altimetry is also severely limited by the inherent trade-off between the spacing of adjacent tracks and the frequency of revisit. Many oceanic phenomena require a higher time-and-space sample rate than is possible from a single satellite. Important examples of these areas of application include observation of mesoscale features, such as eddies and rings in the ocean, and circulation studies along the continental coasts (the littoral regions).

The WITTEX Concept

One of the key measurements derived from radar altimetric data is the slope of the ocean's surface. Such slopes are very small, typically less than 1 cm/km. With only one data track, only one component of the surface slope can be deduced. Clearly, this is not sufficient to characterize the 2-dimensional slope of the surface. Until now, no practical means has been available to measure the cross-track component of slope. WITTEX is a natural response to this need.

Figure 2 illustrates a constellation of three altimeter spacecraft capable of making significant improvements in ocean altimetry. One arrangement would have the satellites spaced by ~200 km along their orbit plane, corresponding to parallel tracks (at the equator) of 12-km spacing. This spacing is sufficient to measure small surface slopes in the cross-track direction. An alternative arrangement would space the satellites by ~900 km along their orbit, which would generate parallel tracks of 50-km spacing at the equator. If the satellites were in the GEOSAT orbit, the resulting track pattern would be like that shown in Figure 3. At the latitude of the Gulf of Mexico, the distance between tracks would be about 45 km. Each set of three adjacent tracks is covered nearly simultaneously by WITTEX, with only a few minutes time spread between passes.

The acronym WITTEX honors E. Witte, who first derived the geostrophic current equations in 1878. It stands for Water Inclination Topography and Technology EXperiment. Indeed, a radar

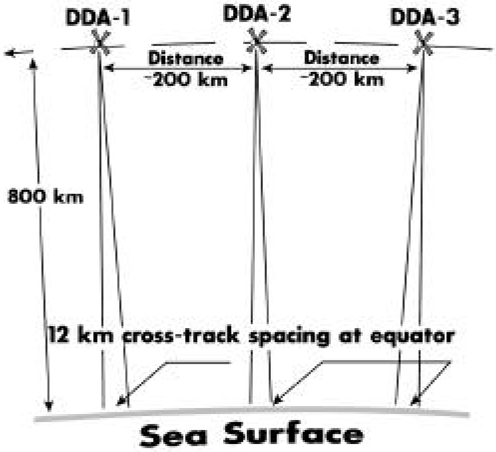

Figure 2. A WITTEX constellation of three radar satellites in one orbital plane as illustrated would provide ocean-height measurements along track as usual, as well as across track on parallel loci separated by 12 km at the equator.

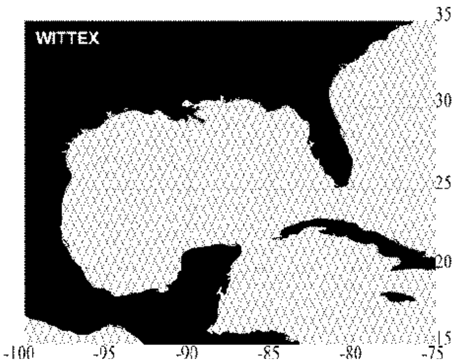

Figure 3. Example of one full cycle of coverage (~17 days) by the WITTEX radar altimeter constellation, where the satellites are about 900 km apart along their orbit plane.

altimeter constellation having this geometry would provide the first means to measure the actual slope vector on the ocean's surface, rather than just one component, which is a limitation of all single-path altimeters.

Although GEOSAT Follow-On is the smallest radar satellite to date, WITTEX satellites would be significantly smaller. Thus, all three satellites could be launched in one payload into the GEOSAT exact repeat orbit. The ability to use a single launch implies that this constellation is far more cost-effective than any multiple-launch configuration. With the instrumentation including a two-frequency altimeter, radiometry, and precision navigation, a TOPEX-class measurement would be achieved. WITTEX would provide the first time-coincident, 2-dimensional surface slope measurements. These would allow unprecedented observations of the ocean's dynamics, including the kinetic energy of the flow fields and the interactions with surface eddies.[4] The increased spatial density of sampling tracks would be especially important for coastal waters.

The Delay-Doppler Radar Altimeter

Unlike all previous space-borne radar altimeters, the DDA technique exploits signal processing algorithms from synthetic aperture radar. Applied to the special case of an ocean-observing altimeter, real-rate onboard processing achieves 10 times more integration of the received signal than is possible in conventional radar altimeters (Figure 4). This translates into a 10-fold reduction in the radiated power required from the transmitter (see Figure 5). The increased signal integration also translates into reduced instrument-imposed variance on the altimeter's principal measurements. Thus, the measurement precision of sea-surface height, significant wave height, and surface reflectivity (which is inverted to deduce wind speed at the surface) are as much as a factor of 2 better than their counterparts from a conventional altimeter.

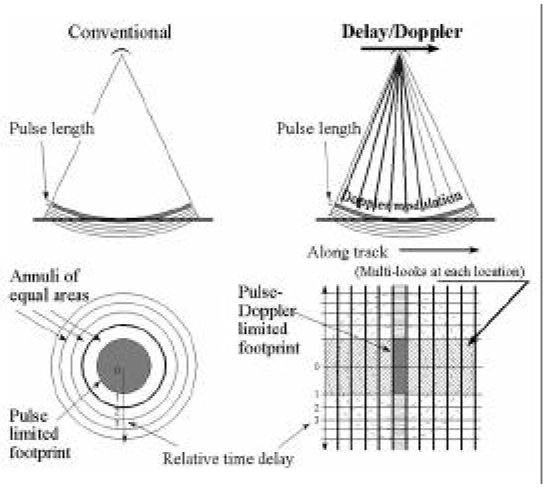

Figure 4. Conventional radar altimeters use the pulse-limited footprint to maintain the required precision. The delay-Doppler implementation uses the additional information associated with the relative movement of the spacecraft to increase the available signal integration, thus reducing power requirements.

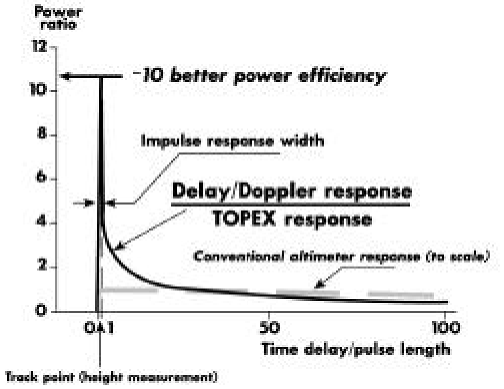

Figure 5. Flat-surface waveform of a DDA compared with a conventional-response waveform. The DDA is able to integrate over much more of the received signal, which translates into a reduction of the required radiated RF power by a factor of 10 in comparison with TOPEX, for example.

III. Technology

JHU/APL has developed a set of strategic principles to guide its Advanced Technology Program, where the central theme is to develop technologies and spacecraft systems that are scalable to a large class of Earth and space science missions at minimal cost. The principles include:

1. Autonomy (simplify and reduce operations cost),
2. Miniaturization (reduce launch and propulsion cost),
3. High reuse architectures (reduce development costs),
4. Instrument innovations (enable new science at lower cost), and
5. Commercial leverage (take advantage of the R&D available in the wider community).

These principles are well aligned with the requirements of WITTEX.

Scalable architecture

A key to major cost savings is the level of reuse that can be achieved in spacecraft design. Our approach to this challenge is to design the fundamental spacecraft architecture to be inherently scalable. That is, the architecture should accommodate larger or smaller demands on the capacity of all onboard resources with minimal changes to the fundamental building blocks (or "primitives") of the spacecraft. Thus, as an example, redundancy (as well as resulting overall reliability) could be increased by adding more copies of the critical primitives in a way that has essentially no impact on the type of elements in the spacecraft block diagram. The primitives themselves must be designed to be standardized building blocks that can be used with minimal design change over a wide range of missions.

JHU/APL is developing the concept with emphasis on the spacecraft electronics that are incorporated into an Integrated Electronics Module (IEM).[5] The IEM uses a common backplane interface (the 1394 backplane has been chosen for future missions). The scalability is achieved by adding resources such as additional processors, solid-state recorder memory, etc. Satellite system interfaces utilize common interfaces such as 1553 and inter-integrated circuit protocol (I^2C). Additional functions, such as global positioning system (GPS) navigation, can be added as needed (as in the TIMED mission[6]). Levels of redundancy and autonomy can be added (or removed). The spacecraft control processor can seamlessly replace a failed system element based on a suitable set of autonomy rules. These rules are layered, with the basic survival rules (such as power shedding) in the hardware, and the more complex and less threatening failures realized in software.

JHU/APL is implementing this concept in the TIMED IEM (see Figure 6). The TIMED IEM has many of the features described above, including the incorporation of the RF up-link and down-link elements and a GPS position measurement system.[7] For TIMED, a PCI bus was substituted for the 1394 protocol bus.

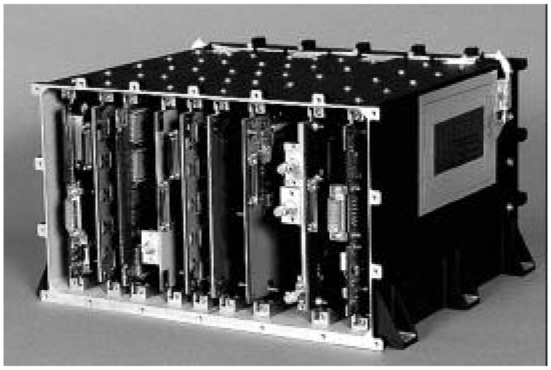

Figure 6. The TIMED IEM.

Miniaturization

One of the major impacts of any multi-satellite approach is the aggregate launch cost. To reduce this cost, a major effort in miniaturization is required. Several approaches to electronics miniaturization are being pursued by both commercial and government research organizations. JHU/APL uses two approaches. The increasing use of custom, very-large-scale integrated technologies for digital, analog, and mixed-signal systems is one approach. Alternatively, chip-on-board (COB) technologies[8] are used to package devices in die form but allow a mixture of other part packaging technologies where cost and/or availability are significant factors.

Techniques are now being developed to decrease the printed circuit feature size to 50 μm. Flip-chip technology using solder, anisotropic conductive adhesive, gold stud-bump, or indium bump provides direct attachment of the chip die to the board. In addition, techniques for embedding passive components within the board are being developed.

Figure 7 identifies the potential savings following both paths. The initial TIMED IEM functionality can be achieved in a volume and mass of approximately one-tenth that of TIMED by using COB and selected application-specific integrated circuits (ASICs). One ASIC under development at JHU/APL is a Bus Interface Unit (BIU), which implements the 1394 backplane protocol. The BIU provides connectivity over two redundant busses for each IEM board in one IC. The BIU does not require a local processor on each board to support the protocol.

A second ASIC under development is a Temperature Remote Input/Output (TRIO) device.[9] This device uses mixed-signal techniques to incorporate both analog and digital circuitry on the same IC to implement a 10-bit A/D converter, analog switching, and digital control circuitry to interface to the I^2C bus protocol.

These elements are being incorporated into the Command and Data Handling In-Your-Palm (CDHIYP) system currently under development. Recent advances in dynamic memories and COB technologies will allow 15-Gbit solid-state recorders implemented in the 10 × 10 cm board format of the CDHIYP system.

New approaches to power system design are being pursued, including the use of new battery technologies that can be built into the spacecraft structure itself. Many of the new battery chemistries, such as lithium ion polymer and the all-plastic batteries that can be molded into conformal shapes, require charge control at the individual cell level. Battery topologies and electronics that can manage the charge with the required precision are being developed as part of an Integrated Power Source (IPS™) technology program.

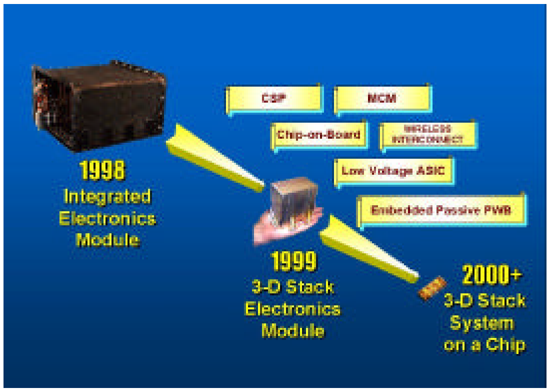

Figure 7. Miniaturization technology will reduce the TIMED version of the IEM by successive orders of magnitude.

JHU/APL and other organizations are developing miniaturized sensors and actuators. These system elements make it possible to reduce the mass, power, and size requirements of the entire attitude control system. JHU/APL has developed a miniaturized camera[10] (see Figure 8) that, when combined with a COB processor and a MEMS gyro, can provide attitude measurements of the precision required for the altimeter mission.

Also, new techniques will allow RF and supporting system elements to be integrated with other electronic functions and miniaturized. The TOPEX altimeter mission flew an ultrastable oscillator (USO) with short-term stability of 10^{-13}(100 sec) having a mass of only 1.2 kg. Advances driven by the Pluto fast-flyby mission can produce an oscillator approaching the TOPEX USO but weighing less than 0.5 kg (Ref. 11) (see Figure 9). These and other advances in miniaturization are expected to lead to spacecraft at least 10 times smaller than current ones, with no loss in performance. These features are incorporated in the WITTEX altimeters and spacecraft described below.

Autonomy

The TIMED spacecraft will take an important step in reducing the ground control requirements by a unique combination of careful

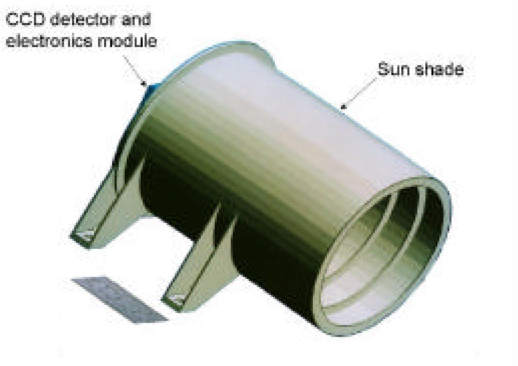

Figure 8. A miniaturized camera, which includes a 1024 × 1024 pixel CCD and COB electronics, weighs 0.5 kg and can provide attitude knowledge of better than 0.05°.

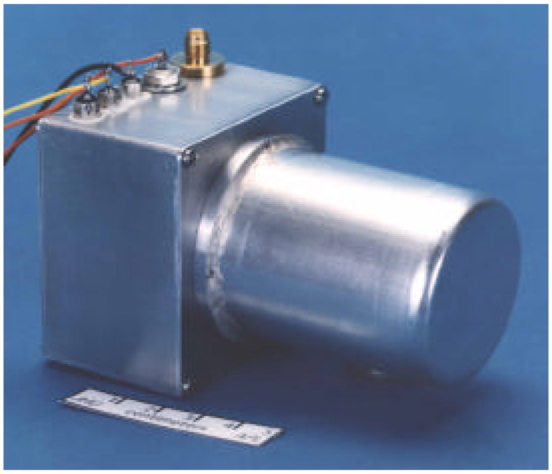

Figure 9. Miniaturized ultrastable oscillator development model with TOPEX-quality stability.

design, onboard GPS processing, and the use of the Internet to move data for each of four instruments from the JHU/APL ground station to each investigator's home institution[12] (see Figure 10). By separating instrument operations from all spacecraft system activities, the instrument teams can control all of the instrument modes, operations, and science data return as their investigation requires without explicit interactions or approvals by the spacecraft project team. In addition, the Internet will provide a simple communications path for the investigators to control their instruments directly. This data and control information will be implemented through packetized messages that are integrated into an automated up-link, command structure. The ultimate goal for TIMED is to develop a "lights-out" concept of operations as the mission progresses. The TIMED paradigm along with lessons learned in the exploitation of commercial satellite constellations, will be invaluable in developing the operational concepts for missions such as WITTEX.

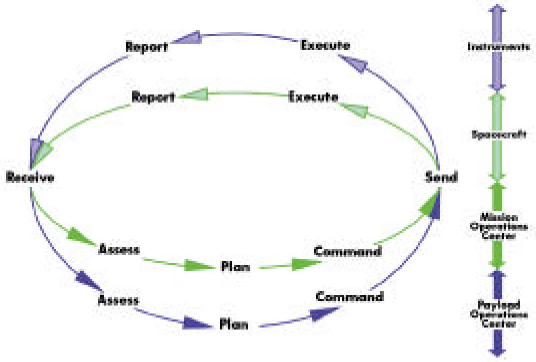

Figure 10. The TIMED mission will be operated via the Internet with control of each instrument by its PI team. Their inputs will be integrated with the spacecraft commands at JHU/APL in an automated fashion and up-linked to the spacecraft. Similarly, the satellite telemetry will be decomutated and transmitted to the PI teams.

Future constellations of spacecraft such as WITTEX will require dynamic knowledge of their relative positions, and preferably they should incorporate autonomous techniques for maintaining their positions or compensating for unwanted position changes. Although several high-precision techniques are being pursued at JHU/APL, the WITTEX mission has less demanding requirements. Satellite spacing tolerance, which is set by the cross-track tolerance requirement, is sufficiently generous that conventional open-loop tracking and station-keeping methods will suffice. The driving requirement for each of the WITTEX spacecraft is precise determination of the orbit's radial component, as is true for any satellite-based altimeter.

IV. WITTEX Implementation

The key to implementation of the delay-Doppler radar altimeter to be used on WITTEX is signal processing. A conventional radar altimeter, such as TOPEX, demodulates (deramps) the signals received from each transmission, applies certain timing and level corrections to each return, and then applies an inverse fast Fourier transform (IFFT) to convert each time history into a power/time height waveform. These are summed together to form the averaged waveform that is subsequently interpreted for science measurements. The DDA algorithm uses the same general approach, augmented by one fundamental additional process. After deramp demodulation, a group of *N* returns is stored in memory. The DDA algorithm applies a set of fast Fourier transforms (FFTs) across each such group. In the resulting deramp/Doppler domain, delay compensation is applied to the data at each Doppler offset in addition to the customary timing and level corrections. An IFFT is then applied to convert each time history into a power/time height waveform. Note that there may be as many as *N* of these elementary waveforms, all generated in parallel. Subsequently, these are summed together to form the output waveform.

This algorithm is ideal for miniaturized implementation. The required RF power, typically only a few watts, is substantially lower than is normally required. Hence the RF electronics, especially the transmitter, can be solid state and small. The receiver, signal generation, and timing controls again can be readily miniaturized. The memory, FFTs, IFFTs, and accumulators can be implemented either through data-driven digital signal processing chips or as conventional routines on a general-purpose microprocessor. The output science data rate would be on the order of 10 kbits/sec, which could be supported by a small data down-link system, or else could be multiplexed onto the data stream from other payload elements. In short, the DDA is an ideal candidate for a constellation of small satellite radar altimeters such as WITTEX.

The DDA makes only modest demands on the spacecraft, as illustrated in Table 1. The processing needs can be accommodated by any one of several devices now becoming available for space use. The majority of the power (~100 W) is required by the two-frequency altimeter and the radiometer. The remaining ~ 30 W are required by the spacecraft. This requirement could be substantially reduced using emerging ultra-low power technology, but reduction does not seem warranted because an array that fits the envelope needs of dual-junction (GaLnP/GaAs) solar cells can develop above 250 W (orbit average).

These requirements can be met by the system delineated in the block diagram of Figure 11. The altimeter electronics would use the 10 × 10 cm card size and COB. The miniaturized reaction wheels, torquer rods, and propulsion elements are within reach of current technology and can provide adequate control authority. Other system elements, such as the frequency reference, star camera assembly, etc., are technologies already established by several different program requirements in the recent past. Ongoing work in JHU/APL's Advanced Technology Program and elsewhere is quickly reducing the size requirements of the RF and other elements to the scales needed for this mission.

Table 1. Mission Requirements.

Attitude control	1^o
Attitude knowledge	0.1°

RF power	5 W
Spacecraft power	Orbit average array power = 250 W Payload operating power = 125 W (Including 100-W radiometer/altimeter and 25 W for spacecraft system)
Altimeter computational requirement	20 MIPS (million instructions per second)
Onboard data storage	15 Gbits per 10 × 10 cm board
Spacecraft position knowledge	2 cm (radial, *ex post facto)*
Altimeter precision	2 cm
Along-track resolution	250 m
Cross-track resolution	2 km
Track repeat	1 km
Track spacing tolerance	1 km
Spacecraft spacing tolerance	10 km

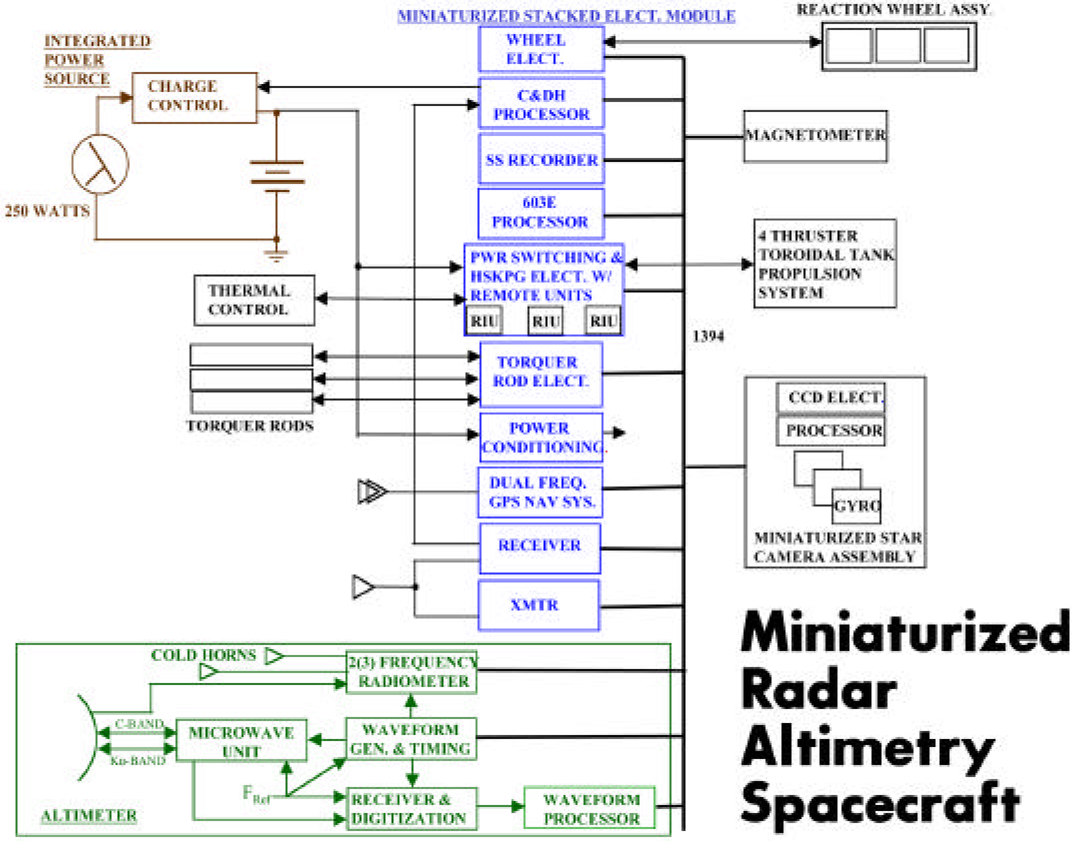

Figure 11. WITTEX altimeter satellite block diagram.

The resulting configuration of a WITTEX altimeter spacecraft is compared to the GEOSAT Follow-On spacecraft in Figure 12.

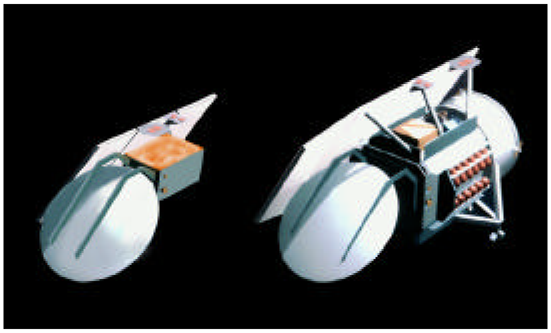

Figure 12. Comparison of a WITTEX altimeter orbital configuration (left) with GEOSAT Follow-On (right), currently the smallest radar altimeter satellite.

Figure 13 shows one stacking arrangement within the fairing of the Pegasus launch vehicle that could accommodate all three WITTEX satellites. Figure 14 presents a possible layout of the satellite system elements within the spacecraft housing.

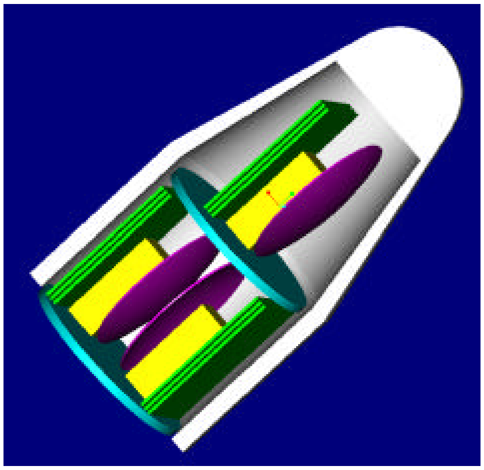

Figure 13. WITTEX launch configuration.

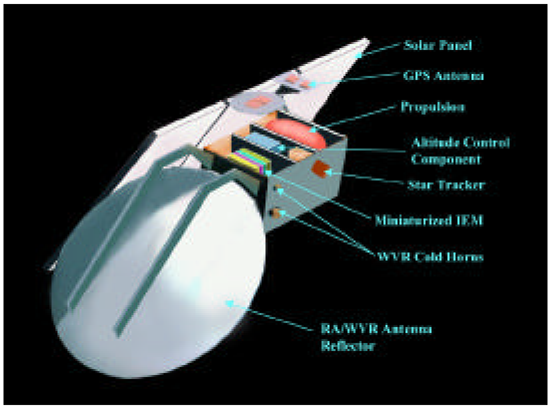

Figure 14. Orbital configuration showing the internal layout of satellite subsystems for WITTEX.

V. Conclusions

The need for a system such as that described by the WITTEX concept is extensive, and this concept offers a variety of benefits. The delay-Doppler technique provides the key to significant reduction in transmitted power. Advanced technologies now being developed by JHU/APL are enabling the miniaturization of spacecraft sufficient to contemplate the simultaneous launch of three high-performance radar altimeter spacecraft.

Acknowledgments. Many people provided the underpinning technical advancements, and the ideas expounded here are only representative. The altimeter constellation concept rests solidly not only on the advancements made by the authors, but also on the work of other key individuals who have provided essential support. These people include Binh Le, Sharon Ling, and Paul Schwartz for system and packaging concepts. Robert Jensen and Paul Marth provided the requirements of GEOSAT and TOPEX and translated them into nominal specifications for the WITTEX mission. The NASA technology program and JHU/APL internal research and development provided the funding for the underlying technologies.

References

1. Special Issues, *The Johns Hopkins APL Technical Digest*, Vol. 8, No. 2, 1987; Vol. 10, No. 4, 1989.

2. Marth, P. C., J. R. Jenson, C. C. Kilgus, J. A. Perschy, J. L. MacArthur, et al. "Prelaunch Performance of the NASA Altimeter for the TOPEX/Poseidon Project," *IEEE Transactions Geoscience and Remote Sensing,* Vol. 31, No. 2., pp. 315–332, 1993.
3. Raney, R. K., "The Delay Doppler Radar Altimeter," *IEEE Transactions Geoscience and Remote Sensing,* Vol. 36, No. 5, pp. 1578–1588, 1998.
4. Stammer, D., and C. Dieterich, "Space-borne Measurements of the Time-Dependent Geostrophic Ocean Flow Field," *Journal of Atmospheric and Oceanic Technology*, in press, 1999.
5. Fraeman, M. E., "A Fault-Tolerant Integrated Electronics Module for Small Satellites," *Proceedings of the 11th Annual AIAA/USU Conference on Small Satellites,* SSC97-1-3, Utah State University, Logan, UT, Sept. 15–18, 1997.
6. Kusnierkiewicz, D. Y., "A Description of the TIMED Spacecraft," *AIP Conference Proceedings 387 of the Space Technology and Applications International Forum*, Albuquerque, NM, Vol. 2, pp. 115–122, 1997.
7. Devereux, W., et al., "The TIMED GPS Navigation System (GNS)," *49th International Astronautical Congress,* Melbourne, Australia, Sept. 28–Oct. 2, 1998.
8. Le, B. Q., E. Nhan, R. H. Maurer, R. E. Jenkings, A. L. Lew, H. S. Feldmesser, J. R. Lalnder, "Miniaturization of Space Electronics with Chip-On-Board Technology," *Johns Hopkins APL Technical Digest*, Vol. 20, No. 1, 1999.
9. Paschalidis, N., "A Remote I/O (RIO) Smart Analog-Digital Chip for Next Generation Spacecraft," *12th AIAA/ USU Conference on Small Satellites,* Utah State University, Logan, Utah, Aug. 23–26, 1999.
10. Le, B. Q., P. D. Schwartz, S. X. Ling, K. Strohbehn, and K. Peacock, "A Low-Cost, High-Density Scientific Imager Design with Chip-on-Board Technology for NanoSat Applications," *Proceedings of the International Conference on Integrated Nano/Microtechnology for Space Applications,* Houston, TX, Nov. 1–6, 1998.
11. Norton, J. R., "Advanced Technology Oscillator for Small Spacecraft," *Proceedings of the 1995 IEEE International Frequency Control Symposium*, pp. 614–619 San Francisco, CA, June 2, 1995.
12. Cameron, G. E., "Applying Advanced Technology to Reduce Life-Cycle Costs," *AIP Conference Proceedings 387 of the Space Technology and Applications International Forum*, Albuquerque, NM, Vol. 2, pp. 111–114, 1997.