NAVY GEOSAT FOLLOW-ON (GFO)

ALTIMETRY MISSION

This site last updated on 06/05/2010

The Intelligence, Surveillance and Reconnaissance - Information Operations Program Office (PMW-180, ISR-IO) a part of the Program Executive Office for C4I and Space, located at the Space and Naval Warfare Systems Command's Old Town Campus in San Diego, CA is the sponsor for this web site.

This site was developed for SPAWAR as a component of the GFO Validation and Calibration system. It is maintained by the Computer Sciences Corporation (CSC) as part of its contract with SPAWAR. Our thanks to NOAA for hosting the revised site.

For an overall view of the Navy's activities in METOC go to the Naval METOC Command's own web site.

For more information on GFO, go to the following pages (please note, these pages are being implemented now and may not be available for some days:

- GFO Operational Mission Overview **(Updated 07/02/2005)**
- Overview of the GFO Satellite and its Performance (**Updated 07/02/2005**
- **Details on GFO past and future** The GFO altimetry satellite that was launched in February 1998 was de-orbited in December 2008 and will reenter the atmosphere in the future. SPAWAR has announced that a contract for a new satellite to be called GFO-2 has been signed. GFO-2 is expected to be launched in 2014.
- Payload Calibration and Data Validation **(Updated 01/27/2007)**

GFO Contacts:

- *Mr. Jay L. Finkelstein - Space Systems Consultant to Computer Sciences Corporation*
  [E-mail - finkelsj (at) surffirst dot net or finkelsj (at) compuserve dot com]

- *Mr. Morton Rau -- GFO Project Manager at Computer Sciences Corporation*
  [E-mail - mrau4space (at) earthlink dot net]
- *Mr. John Lillibridge -- GFO contact at NOAA*
  [E-mail -- John dot Lillibridge (at) noaa dot gov]

***Note**: If you need to contact the above, please replace the '(at)' and the 'dot' in the email addresses above with an '@' symbol and a period respectively and remove any extraneous spaces. We are trying to prevent automated programs from skimming email addresses from this site.*

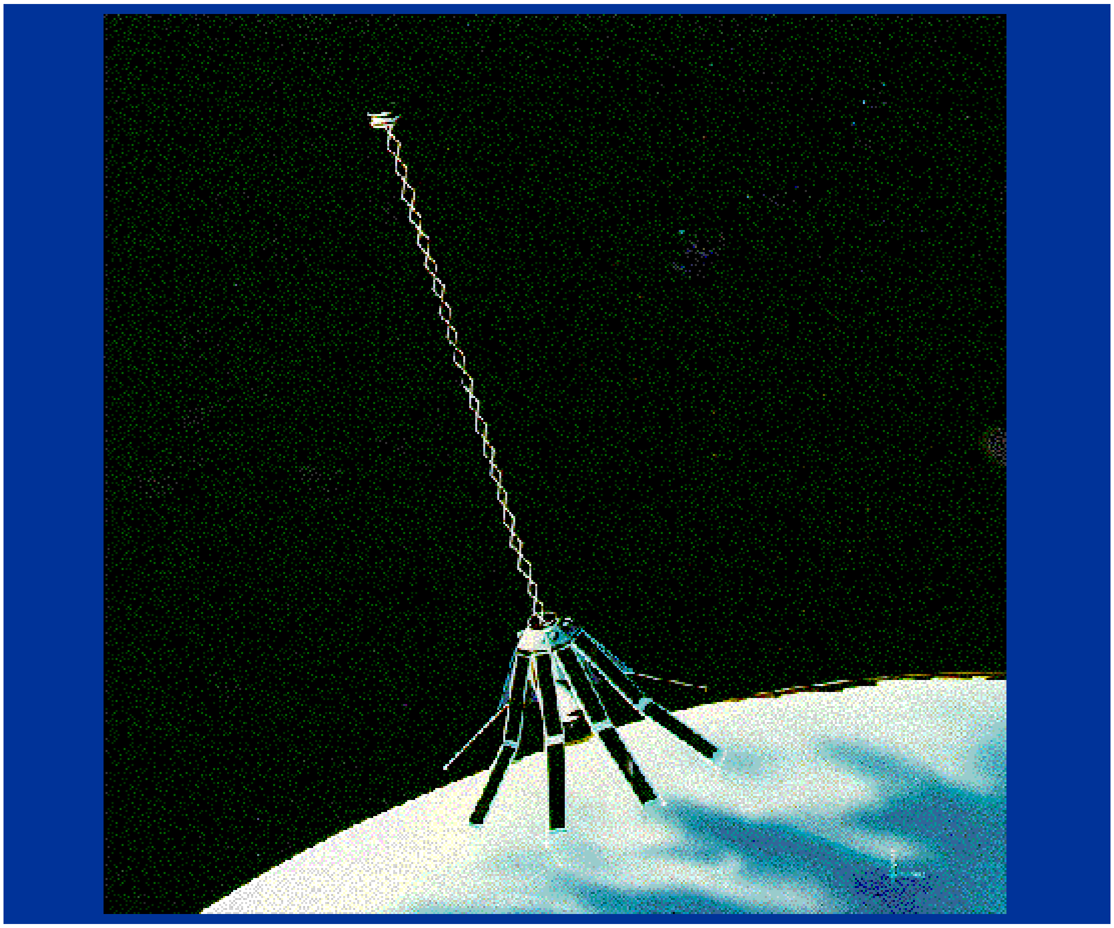
For comments or questions about this Web Site contact Mr. Jay L. Finkelstein at either e-mail address

GFO Mission Overview

The GEOSAT Follow-On (GFO) program is the Navy's initiative to develop an operational series of radar altimeter satellites to maintain continuous ocean observation from the GEOSAT Exact Repeat Orbit. GFO is the follow-on to the highly successful GEOSAT-A and was launched in February 1998. On 29 November 2000 the Navy accepted the satellite as operational.

The Navy GEOSAT Mission

The 5-year GEOSAT mission and its extensive data validation program demonstrated the ability of the radar altimeter to measure the dynamic topography of the Western Boundary currents and their associated rings and eddies, to provide sea surface height data for assimilation into numerical models, and to map the progression of El Nino in the equatorial Pacific. Descriptions of the GEOSAT system characteristics were collected in two special issues of the *Johns Hopkins APL Technical Digest* (Ref. 1). Extensive references and collections of ocean science results were presented in special issues of the *Journal of Geophysical Research* devoted to GEOSAT (Ref. 2).



References:

1. Vol. 8, No. 2, April-June 1987; Vol. 10, No. 4, October-December 1989.
2. Vol. 95, No. C3, March 15, 1990; Vol. 95, No. C10, October 15, 1990.

Program Management

The METOC Systems Office of the Space and Naval Warfare Systems Command has overall responsibility for executing the procurement and operations of the Navy's environmental sensor satellite.

Why GFO , GFO Satellite and Mission Design,

---- return to GFO front page ----

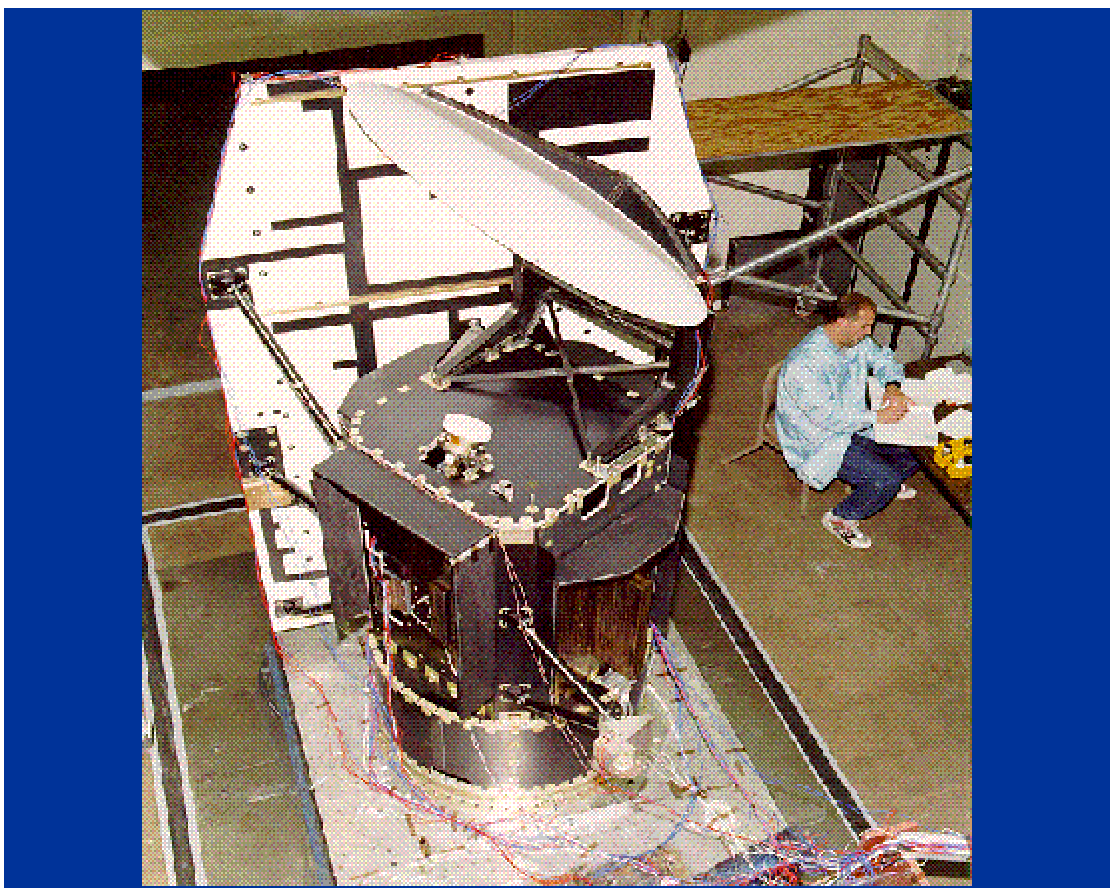
GFO Satellite Overview

This page was last updated on 07/02/05

The Navy Prime Contract for the GFO system design, production, and test was awarded by the Space and Naval Warfare Systems Command in August 1992. The system elements included the satellite, payloads, launch vehicle and updates to the Navy Satellite Ground System. The finished GFO satellite was launched on 10 February 1998, and accepted on 29 November 2000. The satellite and the ground system are now operational.

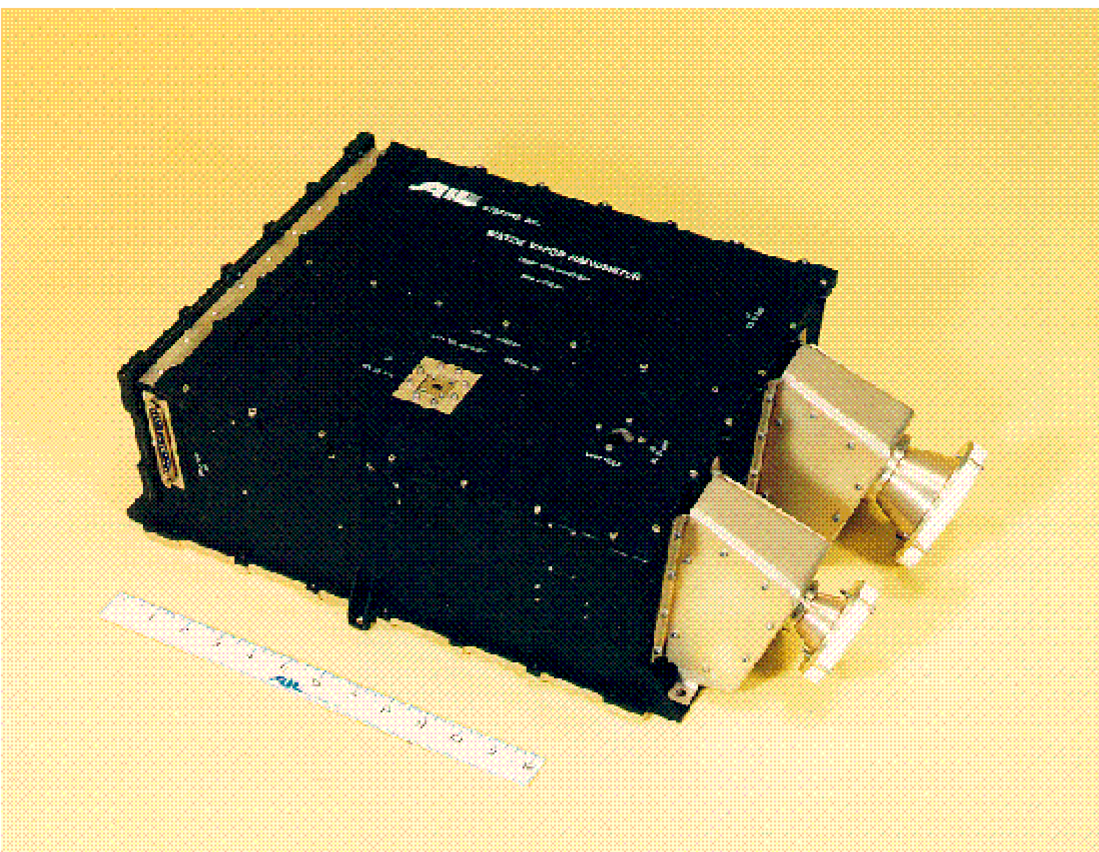
A summary of the performance to date of the GFO spacecraft on-orbit is posted on the Performance Summary Page. The chart on that page gives an overview of the on-orbit performance of the satellite and with a hyperlink to information on any satellite or ground-system anomalies.

- **GFO Spacecraft**
  The image below shows the spacecraft structure during its Modal Survey and Vibration testing

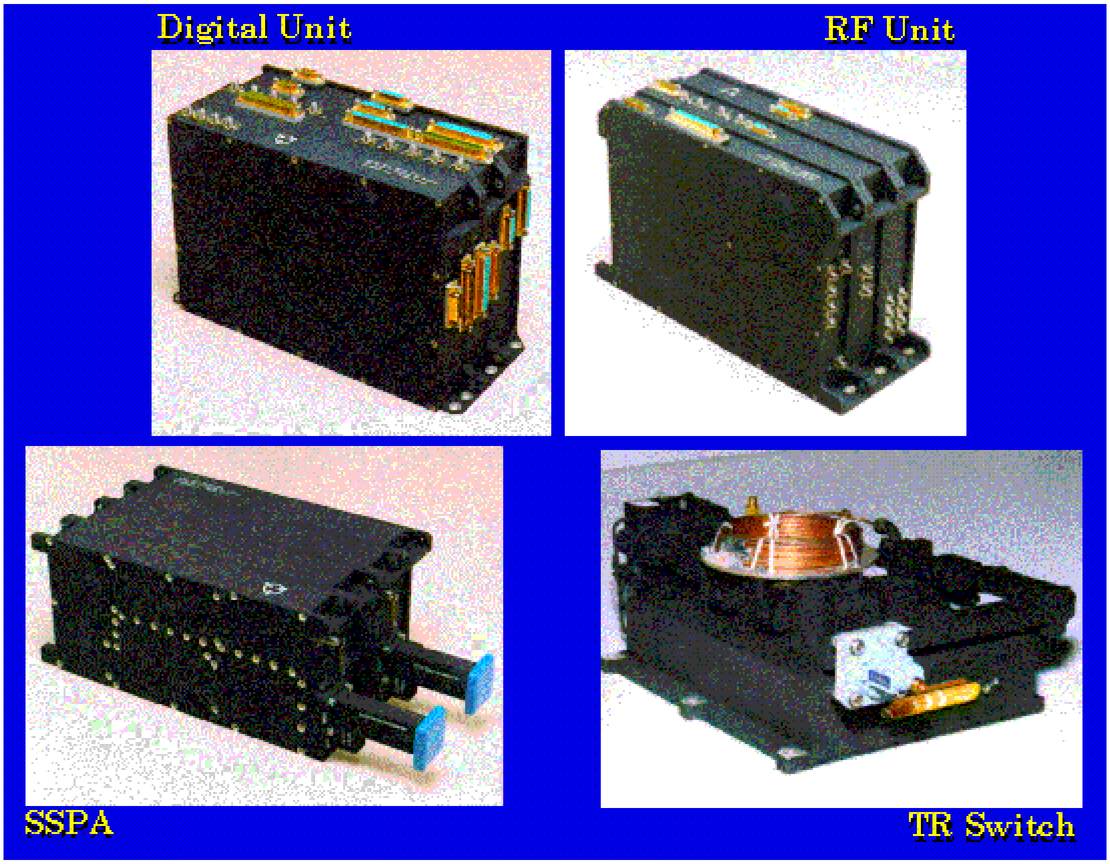


- **GFO Launch Vehicle - TAURUS**
  This image shows the expendable launch vehicle on the launch pad at Vandenberg Air Force Base prior to the 10 February launch.

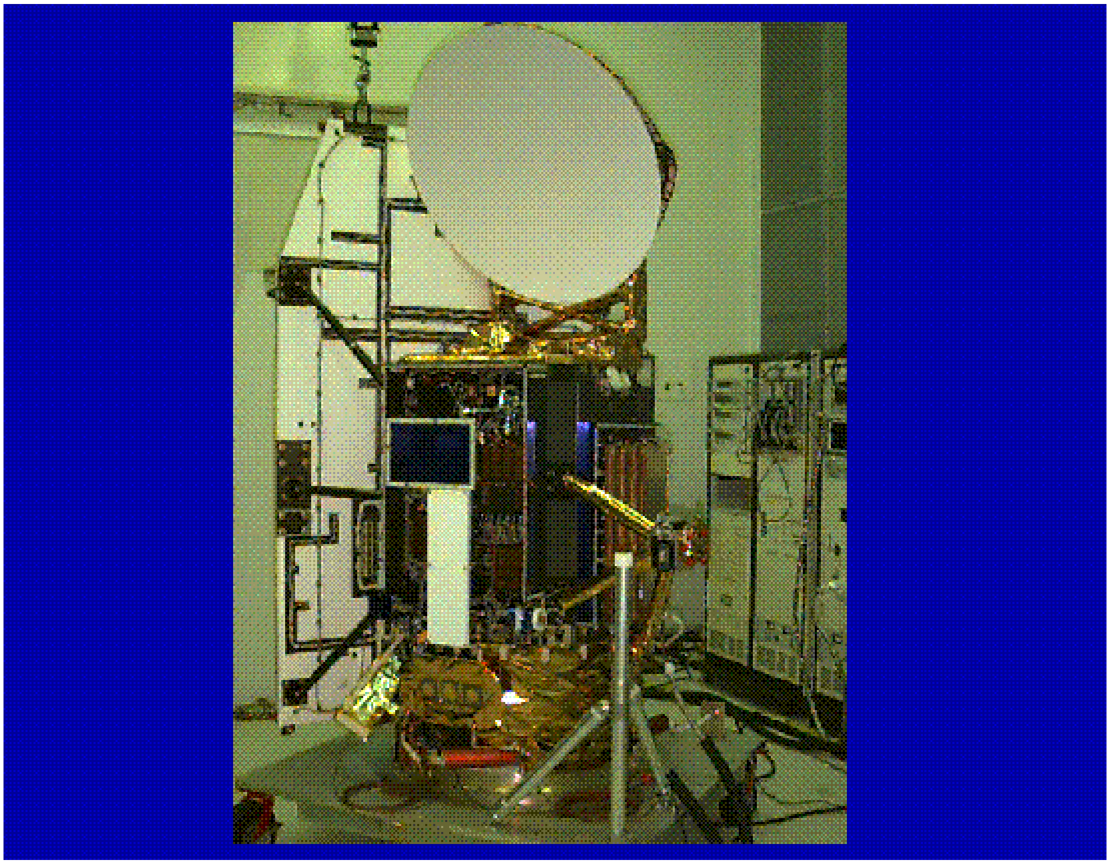
- **GFO Radiometer**
  This image shows the water vapor microwave radiometer flight unit ready for spacecraft integration.



- **GFO Altimeter**
  This image shows the all solid state microwave radar altimeter flight unit ready for spacecraft integration.



- **GFO Spacecraft**
  This shows the integrated spacecraft during its system testing.



--- return to GFO front page ---

Program and Operations Status Report

Updated on 01/25/2010

The GEOSAT Follow-On satellite altimeter sponsored by the Oceanographer of the Navy was launched 10 February 1998. Several difficult problems including confounding interactions between CPU and compiler versions prevented the satellite from running consistently until they were overcome through the intense work and dedication of NAVSOC (The Naval Space Operational Command), the Cal/Val team, Ball Aerospace (the prime contractor for the spacecraft) , in addition to researchers in academia and government laboratories such as the NOAA Laboratory for Satellite Altimetry.

The GPS receivers onboard never achieved operational use. Fortunately, NASA had provided a laser retro-reflector for the satellite prior to launch and the International Laser Ranging Service (ILRS) provided tracking from its global network of laser ranging stations to support the project. Thus high accuracy orbits were provided for the satellite in addition to the orbit solutions based on the on-board Doppler beacon. (For additional details on ILRS, go to http://ilrs.gsfc.nasa.gov.) Precise time was provided by synchronizing the drift of the on-board Ultra-Stable Oscillator to NAVSOC ground systems.

GFO was accepted by the Navy in 2000. NAVSOC ran the spacecraft during its lifetime, and the data was processed daily at the Naval Oceanographic Office.

In summary, there were several critical failures that would have ended the mission before useful data were provided if not for the passion and dedication of many individuals and organizations that turned the mission into a success.

Through the years, GFO performed extremely well thanks to the continued dedication of the people noted above. The data provided by GFO has been used by operational centers to assimilate into numerical prediction systems that in both research and operational modes provided critical information such as currents and ocean environment structure during many incidents throughout the globe. The data flow was a necessary contributor to moving ocean forecasting from the point of a theoretical possibility on which we could conjecture to a solid demonstration of the feasibility and what the capability can provide and to the point of implementation into operational forecast centers. It has proved a great success especially since the entire mission was accomplished on a total budget of $85M. The continued monitoring and careful guidance from NAVSOC, the Cal/Val team, and Ball Aerospace engineers allowed the satellite to outlive its original predicted life of 8 years. Degradation of battery capability and attitude control sensitivity to heat excursions brought the satellite system to the point where it was no longer maintainable. The decision was made to de-orbit the satellite at the end of 2008. All those who contributed can be proud of what they have achieved.

In memoriam, we would also like to remember the contributions of two individuals who helped make the mission successful: Jimmy Mitchell and Vince Noble -- they are no longer with us, but their names are inscribed on a plaque on the satellite.

Many of us will keep a little space in our hearts and a little space on our disk drives for the GFO data from "the little satellite that could".

Added Note: For those who are not part of DoD: ***All*** GFO altimetry data was authorized for unconditional (and unclassified) release by SPAWAR. Hence all GFO data (SDRs, GDRs and raw data over some ice areas) was forwarded to NOAA (and NASA) for distribution and use by the civilian community. NOAA used the SDRs along with the Medium Laser orbit data from NASA to produce an independent set of GDRs known as the IGDRs. For non-DoD users, NOAA is the formal point of contact for data dissemination. If you are not part of DoD and wish access to GFO data, please contact John Lillibridge.

Future Plans -- the Space and Naval Warfare Systems Command in San Diego intends to launch a new version of this satellite to be known as GFO-2. It is expected to be available in 2013.

For reference, the nominal GFO satellite ERO orbit parameters are:

Semi Major Axis	**7162.62 Km.**
Eccentricity	**0.0008035**
Inclination	**108.0448 deg.**
Argument of Perigee	**90.5350 deg.**

--- Return to GFO front page ---

Payload Calibration and Data Validation

Updated 07/02/05

For information on the SDR and NGDR products go to: [Data Product Formats]

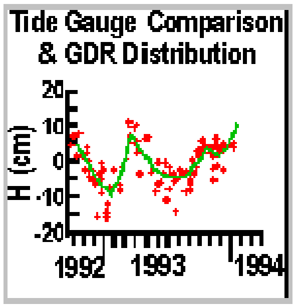
For a description of the current GFO timing system go to: [System Time Management]

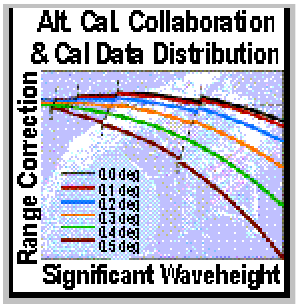
To delineate the flow of data through the GFO program to those efforts go to [Data Flow]

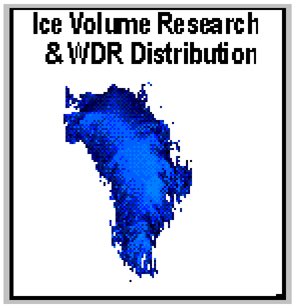
For a description of the Cal/Val plan and its players, go to the [GFO Calibration, Validation and Quality Control Plan] (updated 7/02/05)

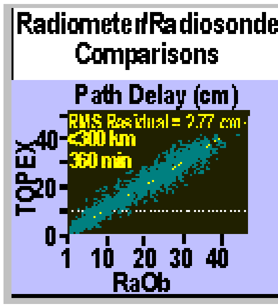
For information on the activities associated with the calibration and validation effort use the buttons/images/hyperlinks below.

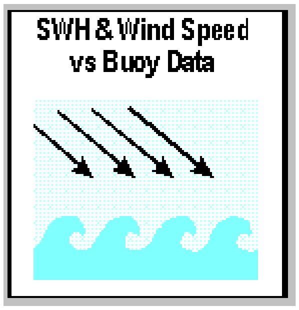
Payload Calibration and Data Validation

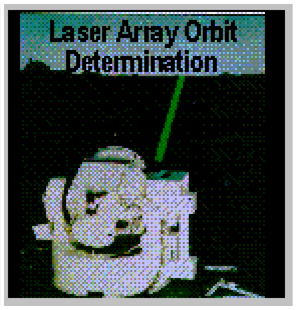


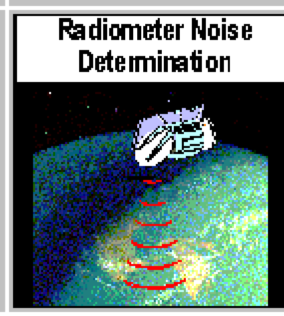


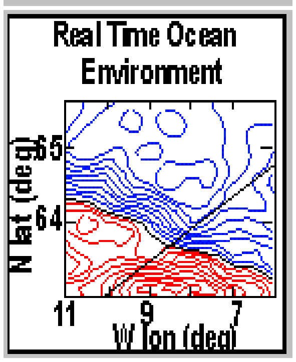


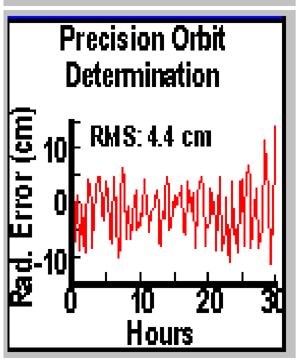


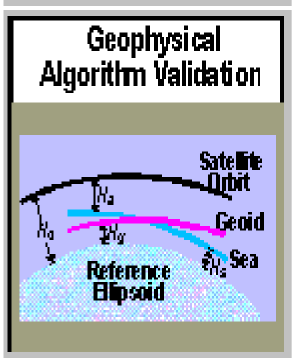












Ohio State WebSite

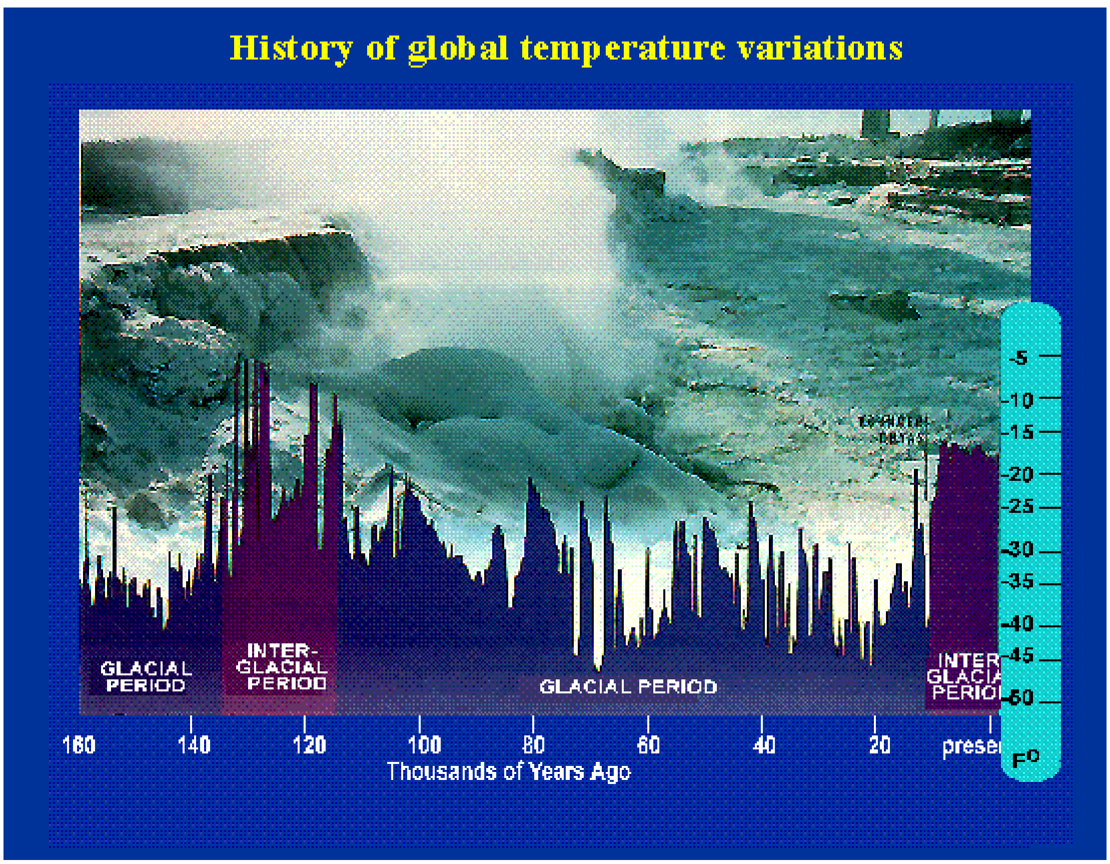
[--- return to GFO front page ---]

Why GFO?

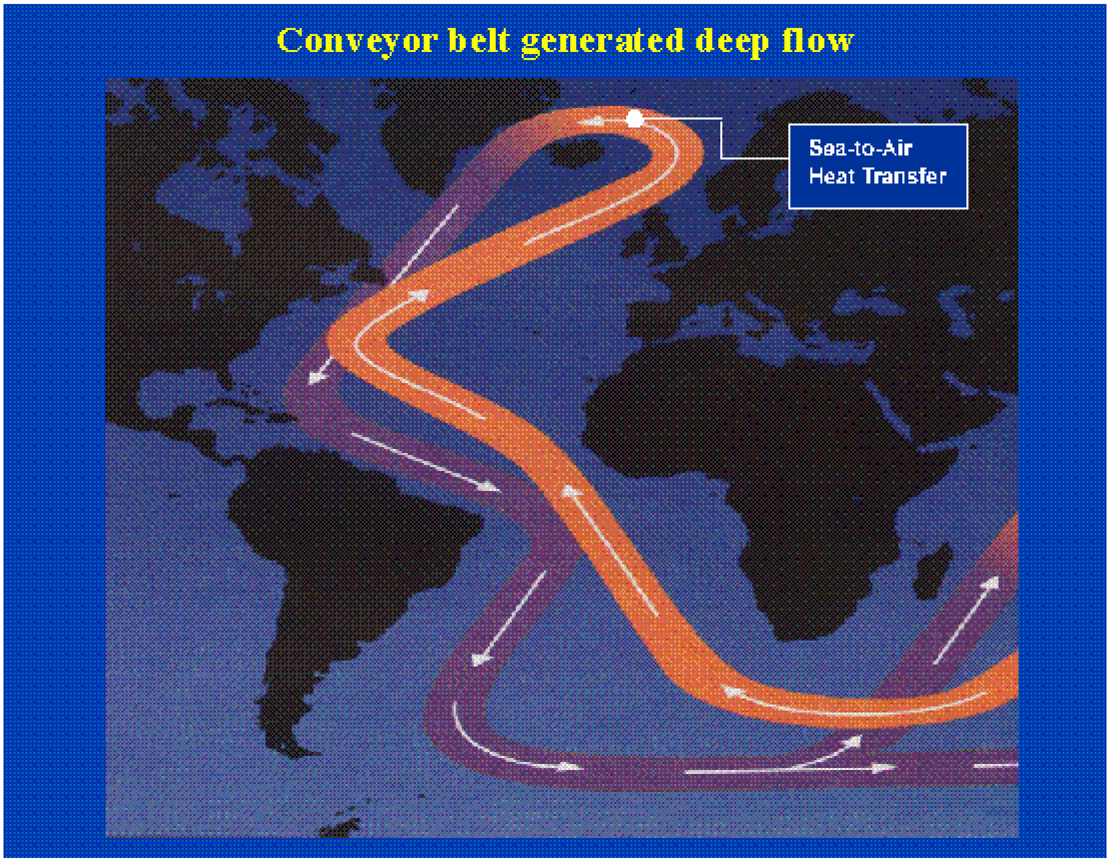
Navy requirements for geodetic and oceanographic information have been a driving force through the history of satellite radar altimetry. The Navy's collection of geodetic information was initially acquired by ship surveys which were slow, expensive, and, incomplete. Now, space-borne altimeters provide a more efficient method of collecting the necessary information to support its environmental predictions and enhance its warfighting capability.

Navy applications of GFO will include use of altimeter data in coastal oceanography, in mapping mesoscale fronts and eddies, and, in using basin-scale data for generating eddy-resolving global ocean models. The length and time scales of these processes are too large for conventional in-the-water oceanographic instrumentation configurations to measure. Satellite altimetry is the only known method by which oceanographers can precisely measure sea surface topography. The shape of the sea surface is the only physical variable directly measurable from space that is directly and simply connected to the large-scale movement of water and the total mass and volume of the ocean.

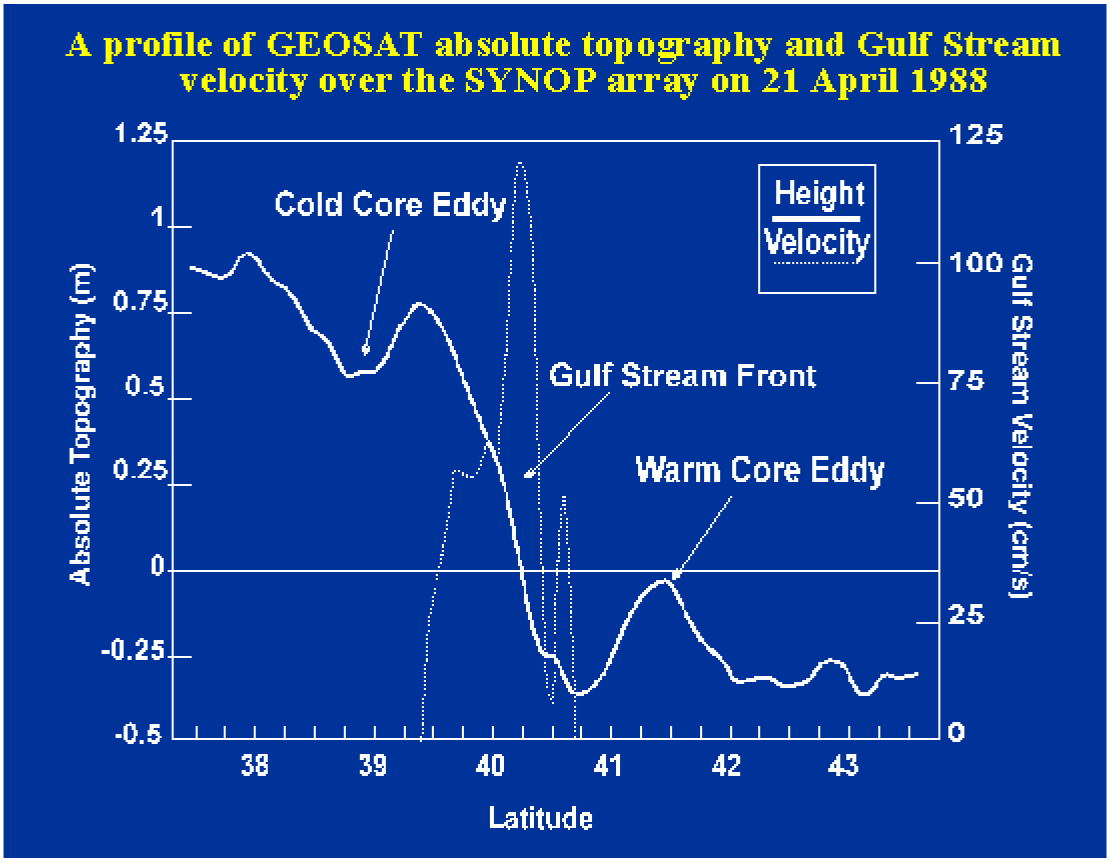
The GFO Mission will support Navy, NOAA, NASA, and University ocean science and ocean monitoring. It is believed that ocean circulation may be a major cause of decadal climate change. New scientific evidence indicates that dramatic, even catastrophic climate changes can occur over the space of only a few years. Recent ice core samples support several models where shifts of as much as 10 degrees Celcius occur in as short a time as 3-5 years. By comparison, the "little ice age" of 750 years ago resulted from a climate change of only 2 degrees Celsius.



Habitable temperatures in the North Atlantic region is due primarily to flow of warmer surface water. As water flows north is becomes more dense and saline through evaporation. Part of the flow sinks and flows south as deep water currents. The remainder flows east toward the United Kingdom before turning south as a surface current. Rising global temperatures could cause high volumes of melt-water from ice caps to alter the density and salinity in North Atlantic waters. This might dramatically change the deep and surface circulation of the water leading to drastic climate changes in North America and Europe. NOAA has established the prediction of decadal climate as a major strategic goal.



The measurement performance of the satellite altimeter has been extensively validated. During the Synoptic Ocean Prediction (SYNOP) experiment, an aircraft under-flight of a GEOSAT pass dropped Air Expendable Bathythermographs (AXBT's). The rms difference in absolute topography between the altimeter and the AXBT's of 6.8 cm when processing the altimeter data with a "synthetic geoid" to provide a precise surface of no motion at mesoscale wavelengths. The GEOSAT data below was provided by JHU/APL.



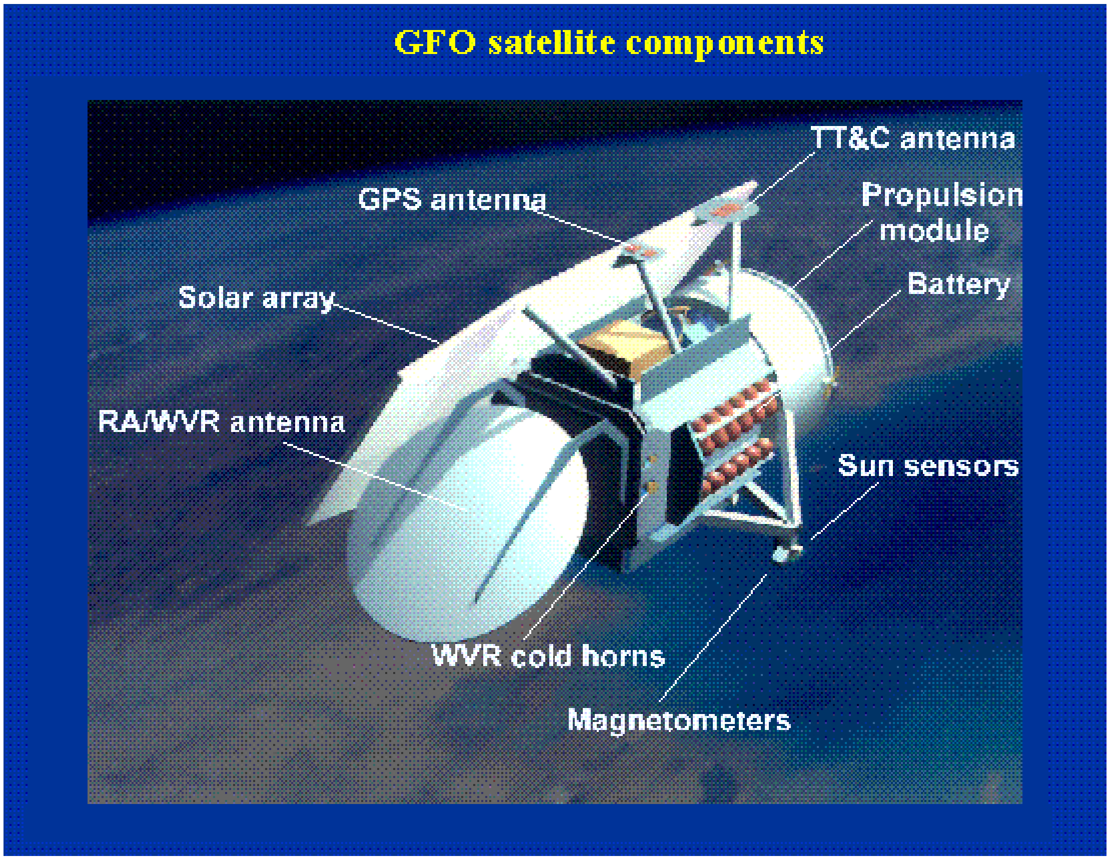
[---- more ----]

[---- return to GFO front page ----]

The GFO Spacecraft and Mission Design

The GFO satellite includes all the capabilities necessary for the precise measurement of both mesoscale and basin-scale oceanography. A water vapor radiometer has been added to the basic GEOSAT measurement capability. GFO also included GPS receivers but these are not working.

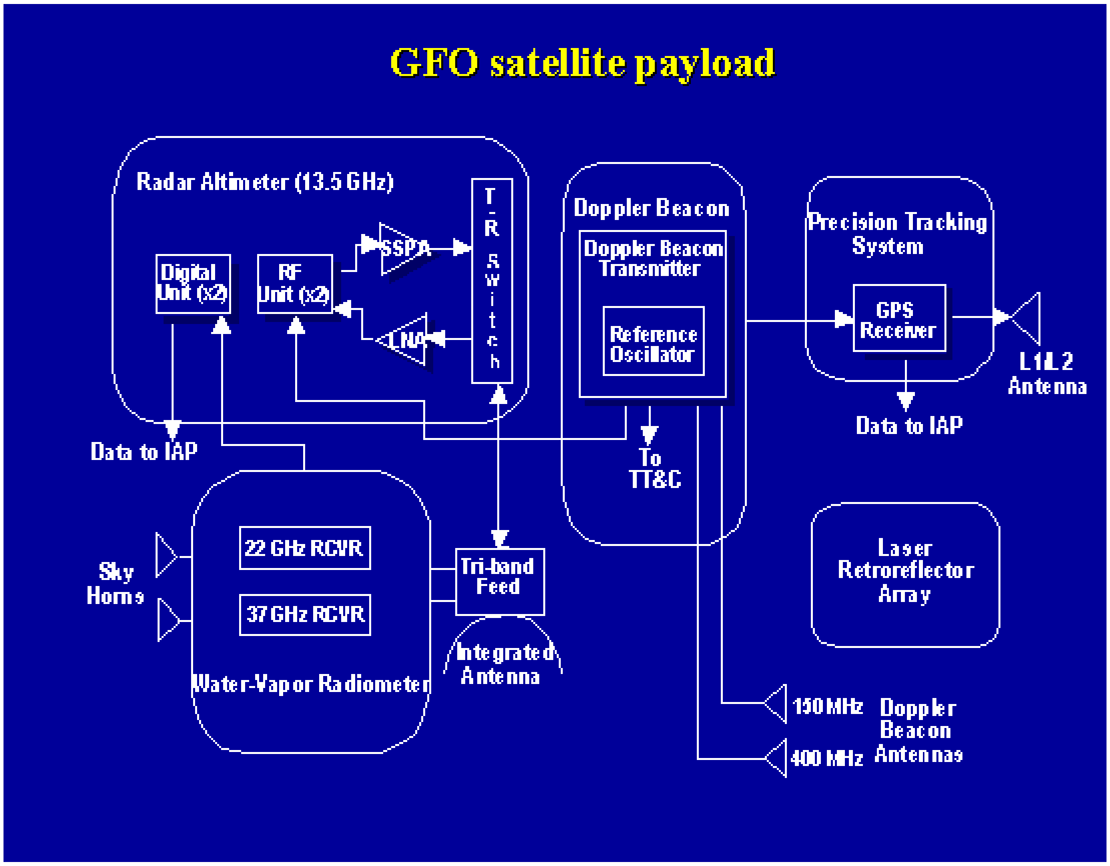
GFO was launched aboard a TAURUS launch vehicle on 10 February 1998 from Vandenberg Air Force Base in California. The launch was near the minimum of the solar cycle. The satellite was accepted by the Navy on 29 November 2000. During its mission life, the satellite will be retained in the GEOSAT Exact Repeat Mission (ERM) orbit (800 km altitude, 108 degree inclination, 0.001 eccentricity, and, 100 min period). This 17-day Exact Repeat Orbit (ERO) retraces the ERM ground track to +/-1 km. As with the original GEOSAT ERM, the data will be available for ocean science through NOAA/NOS and NOAA/NESDIS.



The 300-kg spacecraft is approximately 3-m long and supports the following payloads:

1. Radar Altimeter - single frequency (13.5 GHz) with 3.5-cm height precision.
2. Water Vapor Radiometer - dual frequency (22 and 37 GHz) nadir-looking with a path correction accuracy of 1.9 cm rms.
3. GPS Receivers – Not working
4. Doppler Beacon - GEOSAT performance-stable oscillators and doppler beacons will allow operational orbits to be determined with 1.8-cm rms radial orbit error for mesoscale oceanography (after tilt and bias removal along a 3000-km arc-filter length.

The payloads will feature complete redundancy, light weight (47 kg total), and low power consumption (121 W total).


GFO satellite payload
Radar Altimeter (13.5 GHz)
Digital Unit (x2)
RF Unit (x2)
SSPA
LNA
T-R Switch
Data to IAP
22 GHz RCVR
37 GHz RCVR
Sky Horns
Water-Vapor Radiometer
Tri-band Feed
Integrated Antenna
Doppler Beacon
Doppler Beacon Transmitter
Reference Oscillator
To TT&C
Precision Tracking System
GPS Receiver
L1/L2 Antenna
Data to IAP
Laser Retroreflector Array
150 MHz
400 MHz
Doppler Beacon Antennas

[---- more ----]

SATELLITE PERFORMANCE SUMMARY FOR 2005

FOR THE CURRENT 17 DAY CYCLES

Updated 07/02/05

BACKGROUND

The Navy is tracking the performance of the satellite since it was accepted on 29 November 2000. The first 17-day Cycle after acceptance by the Navy is numbered 000 and is used as a reference for the succeeding cycles. The 17-day Cycle which started on December 16, 2000 (Julian day 352) is the beginning of the first evaluation cycle, Cycle 001, which ended on 2 January 2001 (Julian day 2001 002). Each subsequent 17 day cycle is consecutively numbered. The Navy is also tracking any system anomalies such as component failures, required use of redundant systems, and existence of permanent/intermittent loss conditions. The results are shown on the System Anomaly page (Updated 07/02/05)

Performance of the satellite and its sensors is tracked by four effectiveness measures, Coverage, Tracking System Precision, Radar Altimeter (RA) Precision, and Water Vapor Radar (WVR) Precision. These measures are calculated as follows:

- *Coverage* -- The coverage is determined for each 17-day cycle by a summation of the over water crossover points in the NAVY Geophysical Data Records (NGDRs) that corresponded to Sensor Data Records (SDRs) from the Ball provided POC which have the altimeter in fine track and which are not flagged as bad (missing, incomplete, out-of-range, etc) for both the ascending and descending arcs. The result is compared with the maximum possible number of over water crossovers. The ratio of these two numbers expressed as a percentage is the measure of system coverage.

- *Tracking System Precision* - The precision of the tracking system is determined by computing the global mean square of the altimeter crossover residuals for a 17-day cycle. The Tracking System Precision is defined as the mesoscale component of this (predominantly) long wavelength error. Although originally applied only to the Doppler system, with the failure of the GPS on-board receivers and the reliance on the medium quality laser generated orbits, this measure is now being applied to the MOE data.

- *Radar Altimeter Precision* - The altimeter precision is determined as the high frequency limit of the altimeter noise spectrum using collinear track differences. The result is reported as the world-wide equivalent white noise standard deviation on the 1 second average ranges. The procedure includes editing of isolated noise spikes and avoidance of areas with high significant wave height.

- *Water Vapor Radiometer Precision* - The radiometer precision (radiometer white noise) is determined in the same manner as the altimeter precision with power spectra derived from multiple individual tracks rather than collinear track differences. The result is calculated as the world-wide equivalent white noise standard deviation on the 1 second samples of integrated atmospheric water vapor in kg/sq m and converted to the corresponding white noise standard deviation on the path length in cm (0.16 kg/sq m is equivalent to 0.1 cm). This procedure includes editing of areas over land and ice and areas of heavy rainfall.

PERFORMANCE TO DATE

PERFORMANCE SUMMARY						
Cycle Number	**Julian Days**	**Coverage (%)**	**Tracking Precision (cm)**	**Altimeter Precision (cm)**	**Radiometer Precision (cm)**	**Notes**
081	**04 251 - 04 267**	**65.1**	**11.0**	**2.84**	**0.105**	**39**
082	**04 268 - 04 284**	**94.4**	**10.0**	**2.66**	**0.114**	
083	**04 285 - 04 301**	**94.1**	**12.0**	**3.08**	**0.119**	
084	**04 302 - 04 318**	**94.5**	**28.0**	**3.08**	**0.122**	
085	**04 319 - 04 335**	**94.7**	**12.0**	**2.98**	**0.132**	
086	**04 336 - 04 352**	**95.0**	**10.0**	**3.36**	**0.121**	**40**

087	**04 353 - 05 003**	**94.8**	**10.0**	**2.86**	**0.138**	
088	**05 004 - 05 020**	**81.1**	**12.0**	**2.71**	**0.122**	**41**
089	**05 021 - 05 037**	**94.8**	**10.0**	**2.72**	**0.110**	
090	**05 038 - 05 054**	**94.2**	**11.0**	**3.15**	**0.127**	
091	**05 055 - 05 071**	**94.3**	**11.0**	**2.56**	**0.135**	
092	**05 072 - 05 088**	**94.2**	**10.0**	**2.78**	**0.120**	

FOR THE PERFORMANCE OF CYCLES 001 to 020, click here

FOR THE PERFORMANCE OF CYCLES 021 to 040, click here

FOR THE PERFORMANCE OF CYCLES 041 to 060, click here

FOR THE PERFORMANCE OF CYCLES 061 to 080, click here

Explanatory Notes

029 - The results for cycle 060 and 061 reflect the fact that the satellite was in its sun-pointing mode with all payloads off for these two cycles. Hence there is no coverage and the other performance measures are undefined.

030 - The coverage result for cycle 062 reflects the fact that the satellite was in its sun-pointing mode with the payloads off for the first day of this cycle (as a continuation of the above event). This reduced the coverage slightly but did not affect the remaining indices.

031 - The coverage result for cycle 064 reflects the fact that the satellite was in its sun-pointing mode with the payloads off for a little over about three days of this cycle (from about 2218Z on day 336 until about 1736Z on day 340). This reduced the coverage but did not affect the remaining indices.

032 - The raw coverage for cycle 065 was 76.2% which reflects that the satellite was coming out of its sun=pointing mode for the first few days of this cycle. The number shown includes an allowance for ground system losses.

033 - The raw coverage for cycle 068 was 90.3%, however an allowance for ground system losses increases the value to 95.3%.

034 - The coverage result for cycle 069 reflects the fact that the satellite was in its sun-pointing mode with the payloads off for the last several days of this cycle to avoid thermal issues with the attitude control wheels. This reduced the coverage but did not affect the remaining indices.

035- The results for cycle 070 and 071 reflect the fact that the satellite was in its sun-pointing mode with all payloads off for these two cycles and into the beginning of cycle 072. Hence there is no coverage and the other performance measures are undefined.

036 - The raw coverage for cycle 072 was 64.0% since the payloads were off during the first few days of the cycle, however an allowance for ground system losses increases the value to 64.1%

037 - The raw coverage for cycle 074 was 93.2%, however an allowance for ground system losses increases the value to 94.8%.

038 - The raw coverage for cycle 077 was 94.1%, however an allowance for ground system losses increases the value to 94.2%

039 - The results for cycle 079, 080 and 081 reflect the fact that the WVR payload was off during the last few days of cycle 79, all of cycle 80 and the beginning of cycle 81 to avoid thermal issues with the attitude control wheels. The indices shown (including coverage) are only for the period when the WVR was on.

040 - The raw coverage for cycle 086 was 94.8%, however an allowance for ground system losses increases the value to 95.0%

041 - The coverage result for cycle 088 reflects the fact that the satellite was in its sun-pointing mode with the payloads off for a about 29 hours of this cycle (about 9 hours at the end of day 05 018 and about 20 hours on day 05 019) due to an attitude control anomaly. This reduced the coverage but did not affect the remaining indices.

SYSTEM TIME MANAGEMENT

GEOSAT TIME MANAGEMENT

The GFO satellite outputs a measure of time onboard the satellite as part of Doppler beacon payload. The onboard satellite time is corrected on the ground to yield an altimeter measurement time for the GFO in a manner similar to the original GEOSAT which utilized a Time Management Unit (TMU) in the APL/JHU ground station.

THE TIME MANAGEMENT "Ratio" PARAMETER

The Doppler Beacon stable oscillator provides the frequency reference for the altimeter and the Vehicle Time Code Word (VTCW) that is used to time tag the data. The frequency of this oscillator and therefore the VTCW clock rate (nominally 1E6 ticks/sec) were initially offset +80 ppm from its nominal value but have drifted with respect to this nominal offset throughout the mission.

The GFO ground system tracks the drift in the stable oscillator offset by measuring the drift in the VTCW. A "Ratio" parameter is defined as the VTCW tick interval, the number of seconds per VTCW tick:

Ratio sec/tick = 1 sec / (1E6 ticks * (1+oscillator offset))

The initial factory setting produces:

Ratio = 1 / (1E6 * (1+80E-6)) = 0.99992E-6 sec/tick

The nominal altimeter timing intervals e.g., the 980 microsecond intervals between measurements, are stated at the nominal clock frequency. The real clock is running faster and so the interval must be reduced by the same (nominally) 80 ppm:

real interval = nominal interval / (1+80E-6) sec

or because of the drift measured by the ratio parameter above, the interval is given exactly by:

measured interval = nominal interval * Ratio * 1E6 sec

TIME BIAS

The parameter Time Bias (initial), included as field 18 in the SDR header, is provided to allow GDR producers and Cal/Val SDR file users to correct time. The bias is a measured parameter, determined from crossovers and collinear differences. *(Note: If this bias is given in satellite time then it must be translated to ground [real] time by ratio*1E6 as shown above. For this and succeeding sections it is assumed that field 18 is already in real [ground] time.)* The bias is applied to data product times as detailed in the following sections. The bias is multiplied by Ratio*1.0E6 in order to account for the offset of the VTCW clock as described in the previous section.

Each Cal/Val file record is labeled with one UTC word, call it UTC_CalVal. The user should apply the time bias as:
UTC_CalVal_Biased = UTC_CalVal - Time_Bias_initial

SDR TIME

Each SDR record is labeled with one Universal Time Code (UTC) word, call it UTC_SDR. The record contains 10 height words, H[0], ..., H[9]. UTC_SDR is the time of H[0], corrected for instrument effects, that is, UTC SDR is the time the satellite is at height H[0]. As derived above, the 10/sec measurement interval is: 0.0980 * Ratio * 1.0E6 seconds, where Ratio (included as field 25 in the SDR Header) accounts for the measured offset of the spacecraft Vehicle Time Code Word (VTCW) from its nominal frequency, 1 MHz.

Time_Bias (initial), included as SDR header field 18, must be applied by the user:
UTC_SDR_Biased = UTC_SDR - Time_Bias_initial

The measurement time of height word H[i], call it UTC_H[i] is:
UTC_H[i] = UTC_SDR_Biased + (i*0.0980*Ratio*1.0E6) seconds
for i = 0, ...,9.

Any record can be time tagged by computing the number of seconds from the time epoch to the beginning of the SDR day (SDR Header field 5) and adding it to the biased record UTC time (time in seconds since midnight).

NGDR TIME

Each NGDR record is labeled with one UTC, call it UTC_NGDR. The record contains one Sea Surface H - Uncorrected height word, derived from the 10 SDR height words by averaging and applying instrument level corrections. These 10 height words are separated by 9 intervals so the measurement time of this word is determined from the corresponding SDR time as:

UTC_NGDR = UTC_SDR + (4.5*0.0980)*Ratio*1.0E6 - Time_Bias_initial.

(Note: By convention the time of the SSH-height word is taken to be the time of the midpoint of the 9 SDR height word intervals.)

SPACECRAFT TO SDR TIME MANAGEMENT

a) VTCW Timing Reference

The Vehicle Time Code Word (VTCW) is the key element of all critical timing functions performed on the GFO spacecraft. The VTCW is a 48 bit ripple counter that is driven by the ultra-stable oscillator in the Doppler Beacon that also drives the altimeter. The VTCW system includes circuits that allow multiple software functions (users) to latch and read the current value of the VTCW. The VTCW is a counter, not a clock.

b) Altimeter Time Tag

When the altimeter outputs a data packet, the VTCW is latched on the leading edge of the "enable" signal, and is appended to the altimeter data.

d) Generating The Spacecraft Clock Correlation File

Software at NAVSOC operates on the telemetry packets and correlates the VTCW counter with UTC (derived from a ground based GPS Receiver). A Spacecraft Clock Correlation file (SCC.dat) is generated that provides the slope and offset needed to convert VTCW to UTC. The file is transmitted to the POCC for SDR generation.

Conceptually, given two UTC times and two corresponding VTCW counter values from the GPS telemetry data, one can determine the ratio derived above as a linear fit:

Ratio = (UTC_2 - UTC_1) / (VTCW_2 - VTCW_1) in UTC sec/VTCW ticks

The SCC.dat file generated contains the Ratio and one UTC_SCC, VTCW_SCC pair, allowing the UTC time for any VTCW to be determined:

UTC = (Ratio * (VTCW-VTCW_SCC) + UTC_SCC) sec

The SCC.dat data used for generating the SDR are included in the SDR Header. For example, a day 98073 SDR Header would have parameters:

UTC year (field 20) = 1998
UTC doy (field 21) = 073
UTC sec (field 23) = 81053.126000
VTCW (field 24) = 742452500.00
Ratio (field 25) = 9.9992E-7

Note that the above Ratio reflects exactly the factory value, the field would have the actual value.

The NAVSOC software implementation for the SCC.dat generation uses a circular file that can hold a maximum of 43,997 UTC/VTCW pairs. Ratio is determined by a linear fit to the available points corrected for telemetry noise. A minimum of three points is required. The earliest VTCW/UTC pair is included in the SCC.dat file and is the base time in this file.

e) Altimeter Range From Time Delay

The GFO altimeter tracks the radar time delay, tau, with a closed loop adaptive algorithm. If the altimeter transmitted a pulse and waited for the return from the surface, the resulting surface time delay, call it tau_surface, would be a direct measure of the range to the surface. In order to increase the ocean sampling rate and reduce height noise, the radar has five pulses in the air at any time, and measures the delay between the most recent pulse generated and the next pulse received (generates 5 pulse intervals ago), call it tau_transmit_receive, and the true range is computed by the SDR software on the ground.

The tracking algorithm operates by first producing a pair of chirp start timing pulses. The first pulse generates the RF transmit chirp (TX_NEW), the second generates the RF LO chirp (RX_NEW) that is mixed with a TX chirp from an earlier chirp pair (TX_OLD), that is returning from the oceans surface. The tracker adjusts the timing between the leading edges of TX_NEW and RX_NEW so that so that RX_NEW aligns with TX_OLD. The time between the leading edges of TX_NEW and RX_NEW (tau_transmit_receive) is output to the spacecraft telemetry system.

In order to compute the actual measurement time, that is, the time when the satellite was at the measured range value, three time corrections must be applied to the time associated with this VTCW:

1. Spacecraft Time Stamp Delay - The time difference between when the altimeter sends tau_transmit_receive to the spacecraft and when the VTCW is applied.
2. Altimeter Hardware/Software Time Delay - Corrects for fixed time delays, the fact that the altimeter is truly at that height half way through the pulse width, and overcompensation of the measured time delay.
3. Range Travel Delay - Back out the TX_OLD chirp travel time to recover the surface delay, tau_surface used to compute the actual height.

The corrections are applied in SDR processing with the equations presented in the following section.

f) SDR Calculation of Data Record Time and Altimeter Height

The following algorithms are used by the SDR software at the POCC to compute altimeter height and data record time:

Each altimeter, WVR, and ancillary sample received at the POC contains a 48 bit VTCW. The VTCW is converted into UTC by using the contents of the satellite clock correlation (scc.dat) file. The process used to convert the VTCW to UTC is:

sample.utc = (clock.ratio * (sample.vtcw - clock.vtcw_value)) + clock.utc_seconds

where:
clock.ratio is from SCC.dat
clock.utc_seconds is from SCC.dat
clock.vtcw_value is from SCC.dat
sample.utc is converted UTC
sample.vtcw is the data sample VTCW

The radar altimeter supplies the Spacecraft Integrated Avionics Processor (S/C IAP) a height word at a regular interval. The S/C IAP assigns a time stamp to that height word some period of time after receiving it. The time tag issue defines the amount of time between the assigned height word time tag and the actual time the satellite was at that particular height. The following process is used to determine when the GFO satellite was at the measured range value:

1. Surface Range Computation:

    tau_transmit_receive = sample.raw_hgt * ecu.hgt_lsb * 1.0E-6

    where:

    - sample.raw_hgt is the raw altimeter tau in counts
    - ecu.hgt_lsb is the conversion from counts into seconds
    - tau_transmit_receive is the raw altimeter tau in seconds

    surface_range = (((tau_transmit_receive+0.0049) * C) * clock.ratio * 1E6) / 2.0

    where:

    - C is velocity of light in mm/sec (SDR Header field 26 * 1E3)
    - the factor 0.0049 adds the time of five 980 microsecond RF duty cycles to convert tau_transmit_receive to tau_surface as described in the previous section.
    - clock.ratio corrects for oscillator offset
    - surface_range is the one-way range to the surface in millimeters

1. Sample UTC Computation:

    sample.utc = sample.utc_uncorrected - spacecraft_time_stamp_delay

    - altimeter_hardware_software_time_delay - range_travel_delay

    - sample.utc_uncorrected is the time associated with this VTCW sample
    - spacecraft_time_stamp_delay is the time difference between when the altimeter sends a height word to the spacecraft and when the spacecraft time stamps it
    - altimeter_hardware_software_time_delay can be shown to be:

      altimeter_hardware_delay - tau_transmit_receive

+ (0.0735-51.2E-6)*clock.ratio*1E6

where:

- altimeter_hardware_delay is of order 100 clock cycles (less than a microsecond) and is neglected,
- tau_transmit_receive equals (2.0*surface_range/C - 0.0049),
- the factor 0.0735*clock.ratio*1E6 is seventy five 980 microsecond pulse repetition times corrected for oscillator offset,
- the factor 51.2E-6*clock.ratio*1E6 is 1/2 the pulse width corrected for oscillator offset.

- range_travel_delay is the one-way travel time between the ocean surface and the satellite antenna and equals surface_range/C.

Combining terms we have:

sample.utc = sample.utc_uncorrected - spacecraft_time_stamp_delay

+ surface_range/C - 0.0783488*clock.ratio*1E6

--- return to Calibration and Validation page ---

Data Flow to GFO Calibration and Validation Activities

The sensor data produced by the GFO Payload Operations Center (POC), co-located with the Altimeter Data Fusion Center (ADFC) at NAVOCEANO, are available to the ADFC within 12 hours of observation. There, the orbits and altimeter range height corrections are combined with the sensor data in an Oracle data base.

The data base fields for GFO orbit information include: the Doppler orbit and the Medium Laser orbit produced at NAVSOC. The ionospheric correction fields include: the JPL Global Ionospheric Model (GIM) plus an error bound. There is a global tide correction using the FES95.1-Grenoble model. Potentially, in the future, other ionospheric and selected regional tide models may be included. In addition, a dry tropospheric correction using the Navy NOGAPS with the TOPEX algorithm, and a wet tropospheric correction determined from the GFO microwave radiometer are also available.

The ADFC will provide for electronic transfer of the required data base fields and other science, engineering, calibration and log data needed for the calibration and validation activities:

- The program is making available to the NASA, NOAA and the calibration and validation team the SDR, NAVO NGDR (using Doppler Orbit data and Medium Laser Orbit data) and CalVal files required for the efforts.
- NOAA is generating GFO IGDRs from the ADFC data base (and Precision Laser Orbit data) for distribution to the science community along with the NAVO generated data. To obtain these GDRs, see the NOAA Tide Gauge Comparisons link on the payload calibration and validation page.
- NASA/GSFC is generating GFO WDRs from the full waveform data provided (by tape transfer) by the ADFC for distribution to the science community. To obtain these WDRs, see the NASA Ice Volume Research link on the payload calibration and validation page.
- NASA/WFF is generating corrections for range and sigma naught as well as calibration results using the ADFC data base fields, the engineering data, the calibration mode data, and the event and command logs all provided by the ADFC. These corrections and calibration results are available to the science community through the NASA Height Drift Calibration link on the payload calibration and validation page.

Abstracts of the efforts with hyperlinks to the Home Pages for each program are provided for additional information and research results.

--- return to Payload Calibration and Validation page ---

A description of the data for the Cal/Val/QC effort discussed in this plan

is provided by the Cal/Val Data Handbook.

GFO CALIBRATION, VALIDATION AND QUALITY CONTROL PLAN

Updated 07/02/05

1.0 INTRODUCTION

Data quality for GFO is ensured through activities in three areas: calibration, validation, and quality assurance. The top level objective of these activities is to characterize and document the accuracy and precision of GFO observations over all relevant temporal and spatial scales, and to monitor the operational output for highly corrupted data, typically caused by processing errors. The plan is organized by GFO payload component activities and is outlined below:

Calibration

Radar Altimeter Calibration

Water Vapor Radiometer Calibration

Doppler Beacon Calibration

Validation

Radar Altimeter Validation

Water Vapor Radiometer Validation

Doppler Beacon Validation

Data Quality Control

Radar Altimeter Data Quality Control

Water Vapor Data Quality Control

Doppler Beacon Data Quality Control

Ground Base Time Tagging Accuracy and Quality Control

Precision Orbit Quality Control

Overall Data Quality Control

2.0 CALIBRATION

The GFO payload calibration constants and the spacecraft information required for calibration will be derived from: 1) laboratory and thermal vacuum pre-launch measurements, and 2) in-flight calibration with on-board systems. Establishing and maintaining payload calibration requires that the following information be available to the CAL/VAL effort continuously during the mission:

- Earth located measurement data.
- Payload data during Calibration and Acquisition mode.
- Payload engineering data.
- Waveform data records during calibration mode and acquisition mode.
- Payload operations data including the payload command log, spacecraft significant event log, and any changes in the Center of Gravity or payload configuration.

2.1 Radar Altimeter Calibration

Altimeter calibration includes the generation of height, height rate, attitude, sea state, and temperature corrections. Also, initial bias offsets that are expected to change slowly after launch, are determined. The altimeter contains on-board calibrate modes, expected to be invoked twice a day, that are designed to track long term drifts and the variation of height with instrument temperature. The altimeter acquisition mode coefficients are adjusted on-orbit to provide data as close to shore as possible to maximize littoral coverage. The following table shows the on-orbit and continuing activities involved:

Factor/Correction	Function	Responsible Party
Altimeter Antenna/CG Offset	-- The offset between the phase center of the altimeter antenna and the Center of Gravity of the satellite shall be determined and updated to account for on-orbit fuel consumption. The initial CG measurement was determined during pre-launch spacecraft testing.	-- One time only (Ball; performed prior to launch).
	-- The updated information required for SDR processing at the POC is generated by the mission operations software at NAVSOC.	-- NAVSOC
Height Correction For Doppler Offset	-- The height measurement of the altimeter is corrected for Doppler-induced offset (characteristic of the linear FM waveform) during SDR processing at the POC. This correction, based on the altimeter operating frequency, uses height rate as an input. The equation will not change over the life of the mission	-- NAVSOC
Calibrate Mode Height Correction	-- The height measurement of the altimeter is corrected for long-term-drift (derived from the on-board calibrate mode CAL I) in SDR level processing at the POC. Every 12 hours the altimeter is commanded to couple a sample of the transmitted pulse into the receiver and track it as a point target. Under normal conditions, this drift is expected to be very small (millimeters of change).	-- NASA/WFF
Calibrate Mode Height Correction For Temperature	-- The height measurement of the altimeter is corrected for instrument temperature in SDR level processing at the POC. Every 12 hours the altimeter will be commanded to couple noise into the receiver and measure the frequency response of the instrument. The height change at moderate SWH resulting from the measured response will be computed by the CAL/VAL team and compared with the applied SDR height correction. One hour of waveforms over water will be taken after each CAL II run and analyzed in order to track small changes in this correction	-- NASA/WFF
Height Correction For Attitude / Sea State	-- Both the ocean SWH and the attitude excursion of the spacecraft change the shape of the measured altimeter waveform, thus introducing a correctable error into the measured height. This correction process begins in the altimeter with the computation of the VATT (Voltage proportional to ATTitude). The relationship of VATT to attitude was determined during pre-launch altimeter testing with simulated ocean returns and the resultant height correction derived from the VATT via an expression which uses a set of wave-height-dependent coefficients. These coefficients were derived before launch using waveform simulations and then updated values are determined from the on-orbit calibration data. The resultant height correction is applied in the SDR level processing at the POC.	-- NASA/WFF
Significant Wave Height Correction For Attitude	-- A correction to the altimeter measurement of significant wave height is applied in SDR processing at the POC. The wave-height-dependent coefficients in the correction expression were derived before launch using waveform simulations and updated values will be determined from on-orbit calibration data.	-- NASA/WFF
Automatic Gain Control Corrections	-- Adjustments are made to the altimeter AGC data in SDR level processing at the POC in order to correctly measure the radar backscatter of the ocean's surface (required for GDR level computation of the Electromagnetic Bias correction). This	-- NASA/WFF

	includes a correction for height variation that affects signal strength, a temperature correction (derived from altimeter thermal vacuum calibration measurements), an attitude/sea state correction, a long-term drift correction (from the on-board calibrate mode), and an initial offset (derived during pre-launch testing) to convert AGC to radar backscatter.	
Acquisition Mode Coefficients	-- Altimeter tracker and acquisition mode performance on-orbit is monitored and updated coefficients generated in order to minimize acquisition time over water.	-- NASA/GSFC
Waveform Sample Gain Corrections	-- A correction is applied to the gain of each waveform sample during SDR level processing at the POC. Initial values were derived for these factors using pre-launch altimeter test data and updated values determined from on-orbit calibration data.	-- NASA/WFF

2.2 Water Vapor Radiometer Calibration

Radiometric calibration includes the generation of parameters for the Antenna Temperature Calibration Algorithm that is used in SDR level processing at the POC to provide measured brightness temperature as a function of the raw radiometer data and the physical temperature of components of the instrument. The radiometer cold horns, hot sources, and temperature sensors provide the periodic calibration data required by the algorithm on orbit. The following table shows the on-orbit and continuing activities involved:

Factor/Correction	Function	Responsible Party
Pre-launch Thermal Vacuum Calibration	-- The radiometer was installed in the Thermal Vacuum chamber with external thermocouples installed on critical components and black bodies over both the feed horn and the cold horns . Calibration data was obtained at +15ºC, +22ºC, and +27ºC. -- Regression analysis was applied to the data and the coefficients for the calibration algorithm derived.	-- One time only, CSC (performed prior to launch) -- One time only, CSC (performed prior to launch)
On-orbit Calibration Adjustments	-- Further improvements in radiometer accuracy by adjustment of the coefficients based on flight data.	-- CSC

2.4 Doppler Beacon Calibration

Factor/Correction	Function	Responsible Party
Doppler Beacon Antenna/CG Offset and Laser Retro-reflector Offset	-- The offsets between the phase center of the Doppler Beacon antenna, the laser retro-reflector, and the Center of Gravity of the satellite is determined and updated to account for on-orbit fuel consumption. This information is required for Operational Orbit Determination at NAVSOC. The required information is generated by the mission operations software.	-- NAVSOC

3.0 DATA VALIDATION

The purpose of the validation activities is to obtain the necessary information to determine the uncertainties associated with GFO geophysical products. This includes work directly with GFO observations, comparisons with data assimilation and ocean models, as well as cross comparisons with other remote sensing systems and in-situ observations.

3.1 Radar Altimeter Data Validation

These activities include the determination of point-to-point noise, system level mesoscale sea surface topography measurement precision, accuracy of basin scale surface variability, TOPEX data comparisons, and the on-orbit stability of calibration constants.

Factor/Correction	Function	Responsible Party
Altimeter Noise Performance	-- The determination of the point-to-point noise on the measured data as reflected by the tails of the power spectral density.	-- CSC

Mesoscale Topography Precision	-- The determination of the capability of GFO to measure mesoscale ocean features by comparison with topography from AXBT data.	-- NRL Stennis
Basin Scale Topography Variability	-- The determination of the capability of GFO to measure basin scale ocean features by comparison with tide gauges.	-- NOAA/NESDIS
TOPEX Crossover Comparison	-- Comparison of GFO and TOPEX system measurement performance by computation of GFO/TOPEX crossover variability.	-- NOAA/NESDIS/OSU/ NASA GSFC
Significant Wave Height And Radar Cross Section Accuracy	-- The capability of GFO to measure significant wave height and radar cross section by comparison with NOAA Data Buoy information. On-orbit changes in these altimeter measurements are monitored using waveform gain monitoring for SWH, and using calibration mode and global averages for the Radar Cross Section (RCS).	-- NASA/WFF
Bias And Calibration Constant Stability	-- Trend analysis will be performed using in-flight altimeter and engineering data in order to assess possible drifts in altimeter corrections and changes in altimeter performance. In-flight updates to the absolute height offset will be determined.	-- NASA/WFF

3.2 Water Vapor Radiometer Data Validation

These activities include the determination of the noise of the radiometer instrument, TOPEX data comparisons, and the system level water vapor measurement accuracy.

Factor/Correction	Function	Responsible Party
Radiometer Instrument Noise	-- Determination of the instrument noise level of the radiometer.	-- CSC
TOPEX Radiometer Comparison	-- Comparison of GFO and TOPEX water vapor measurements at crossovers.	-- CSC
Water Vapor Measurement Accuracy	-- The capability of GFO to measure atmospheric water vapor is measured by comparison with radiosonde launches.	-- CSC

3.4 Doppler Beacon Data Validation

Factor/Correction	Function	Responsible Party
Operational Orbit Determination Precision	-- The precision of the Doppler orbits shall be determined every 17 days by computation of the variance of sea surface topography differences.	-- CSC /OSU

4.0 DATA QUALITY CONTROL

The quality of the GFO data products shall be monitored and controlled by: 1) data quality modules in each processing software package, 2) tracking the quantity of data successfully produced, and 3) tracking the results of the data validation activities. The following table shows the on-orbit and continuing activities involved:

4.1 Radar Altimeter Data Quality Control

Factor/Correction	Function	Responsible Party
Processing Software Quality Flags	-- The SDR software develops a number of data quality flags based on the altimeter status mode bytes and detection criteria for abnormal data. Monitoring these over the mission will provide consistent data sets and allow early detection of processing errors.	-- CSC

Data Validation Results	-- Measurement of the health of the system and quality of the data by altimeter point-to-point noise determination -- Tide gauge comparisons -- Calibration results	-- CSC -- NOAA/NESDIS -- NASA/WFF

4.2 Water Vapor Radiometer Data Quality Control

Factor/Correction	Function	Responsible Party
Processing Software Quality Flags	-- Monitoring of the data in the SDR records is a measure of the processing software quality.	-- CSC
Data Validation Results	-- Measures of the health of the radiometer and quality of the data and the radiosonde comparison	-- CSC

4.4 Doppler Beacon Data Quality Control.

Factor/Correction	Function	Responsible Party
Processing Software Quality Flags	-- Monitoring of the data by the ODP software provides feedback on the quality of the Doppler orbits produced.	-- NAVSOC
Data Validation Results	-- The number of SDR records produced every 17 days as reported provides a measure of the quality of the Doppler beacon data. -- Monitoring of the actual Doppler Frequency is a second measurement	-- CSC -- NOAA/NESDIS

4.5 Ground Base Time Tagging Accuracy and Quality Control

Factor/Correction	Function	Responsible Party
Data Validation Results	-- Ground Based Time Tagging System health and time accuracy by measurement of SCC.DAT time jumps -- Frequency measurements; tracking of height drift	-- CSC -- NAVSOC and NOAA/NESDIS

4.6 Precision Orbit Quality Control

Factor/Correction	Function	Responsible Party
Laser Array Orbit Determination	-- Use of Internal Quality Controls	-- NASA/GSFC
Precision Orbit Determination	-- Provide an independent check of Precision Orbit Quality	-- OSU
Data Validation Results	-- Precision orbit data quality by crossover difference determination -- Internal Quality Controls	-- CSC -- NOAA/NESDIS

4.7 Overall Data Quality Control

Factor/Correction	Function	Responsible Party
Comparison of GFO data with Other systems	-- The use of other system data, independent cross-over analyses, buoys, etc. for determination of GFO improvements	-- OSU
SDR Records Produced	-- The number of SDR records, NGDR(o) records, and NGDR(m) records produced provide a measure of the	-- CSC

	quality of the overall system output.	
Ionospheric Model Calibration and Corrections	-- Based on comparison of GFO output and ionospheric data which is compared to data from other sources such as TOPEX, model corrections and updates are derived	-- OSU

Tide Gauge Comparisons and GDR Distribution

NOAA has accepted the responsibility for generating and distributing the final, research-quality GFO Geophysical Data Records (GDRs). This is in cooperation with the GFO validation team, NASA, JPL, and selected university partners. The GDRs will be based on the SDRs and the interim GDRs produced in near-real time by the Naval Oceanographic Office, but will contain more accurate orbits, corrections, and geophysical models. The NOAA/NESDIS Team, will continually monitor GDR accuracy and consistency using standard methods developed during past altimeter missions. Tests will include crossover and collinear differences together with comparisons with tide gauge data.

NOAA GFO IGDR Data Available for Validation

NOAA is merging the NAVO SDRs with NASA laser precision orbits and geophysical corrections into NOAA GFO IGDRs. This data is available from NOAA/NESDIS.

Some information on the data set:

1. The SDR UTC timestamp has been adjusted by moving it to the midframe (this could be improved, it's just a constant right now).
2. a 46.55 msec time bias has been applied as follows:
   ```
   ----------------------------------------------
   // Remove the incorrect constant correction
   sdr_utc_recovered = sdr_utc + 0.0758988
   // Apply the proper correction using the SDR header Ratio parameter
   sdr_utc_corrected = sdr_utc_recovered - 0.0783488*Ratio*1E6
   // Add bias to account for altimeter timing error
   sdr_utc_biased = sdr_utc_corrected + 0.0490000*Ratio*1E6
   ----------------------------------------------
   ```
   The total change (for Ratio*1E6= 0.99992) is +46.5523 millisec.
3. The SDR header parameter "altitude_bias_initial(km)" is subtracted. It is currently 20.904 meters thereby increasing SSH by 20+ m.
4. The "precision time" version of the SDRs has been used. Time on these SDRs is generated from GFO GPS receiver time.
5. The SLR orbits are spliced together midway between the 1-day overlaps in the 5-day solutions.
6. The data are concatenated into daily files.

The files "gfo_980602.igdr.gz" through "gfo_980610.igdr.gz" are available.

NOAA's collinear analysis, as collaborated by data from the Cal/Val team, shows (as expected) that the SSH differences are 10s of cm (vs. 20 m) and the timing bias is < +/- 1 msec. .

--- return to Payload Calibration and Validation page ---

Altimeter Calibration Collaboration and Cal Data Distribution

At the Wallops Flight Facility (WFF) of NASA's Goddard Space Flight Center (GSFC), calibration collaboration by the Observational Science Branch of GSFC's Laboratory for Hydrospheric Processes analyzes GFO altimeter data to: i) characterize the altimeter's pre-launch performance; ii) monitor changes in the altimeter's in-flight performance; and iii) provide the instrument calibrations (both pre-launch and in-flight updates) needed by the civilian users who require absolute range calibration.

The altimeter science and engineering data is used to refine the corrections to range and sigma naught for the effect of significant wave height and attitude, and the revised corrections will be made available to the Navy, NASA and NOAA. WFF will develop databases for altimeter engineering and science measurements, and will update those databases over the life of GFO, performing trend analyses to assess possible drifts in altimeter measurements. Design and build data (e.g., S/C size, mass and configuration, locations of GPS, Center of Mass, Drag, etc.) are available for use in the civilian GFO precision orbit determination

The Wallops Flight Facility obtains the near-real time NGDRs from GFO's ADFC data base as well as the Waveform Data Records. The engineering data, calibration mode data, altimeter command logs, spacecraft significant event log, and all other data reflecting changes in the Center of Gravity or instrument configuration are also obtained from the ADFC. As part of this effort WFF also participates in the analysis of the ABCAL data to ensure that the satellite attitude control system is correctly optomized.

The WFF calibration activity for GFO is sponsored by NASA Headquarters, Code Y, Office of Mission to Planet Earth.

--- return to Payload Calibration and Validation page ---

Ice Volume Research and Waveform Data Record Distribution

NASA/GSFC is using the GFO data as part of a long-term effort utilizing the unique capability of satellite altimetry to improve our understanding of the Earth's ice sheets and floating ice shelves. Precise measurements of elevation changes over the ice sheets and ice shelves can be used to estimate total mass balance of the ice sheets which has not been obtainable to sufficient accuracy with other techniques. Time series of elevations constructed from the altimetry data can provide detailed information on the seasonal and inter-annual variations in the ice-sheet surface balance, which are caused by variations in snowfall and ice melting.

The GFO program produces altimetry-derived surface elevations over the Earth's ocean that can be used to meet oceanographic and geodetic objectives. To create height elevations over the polar ice sheets and surrounding sea ice that can be used to study mass balance changes and ice sheet dynamics requires additional processing of the altimeter return waveform. The return waveform also contains information on the ice sheet surface characteristics which are being studied to further our understanding of inter-decadal and inter-annual changes.

The GFO altimeter's tracking and acquisition performance will be routinely monitored as part of the waveform processing. Updated coefficients that allow better coarse mode tracking at land/sea interfaces and faster fine track acquisition over water will be generated and provided to the GFO program.

The GFO Program delivers to the NASA/Goddard Space Flight Center (NASA/GSFC) altimeter Waveform Data Records at a rate of 10/sec over the Greenland ice sheet, surrounding sea ice, and some other areas as may be mutually agreed upon between NASA and the Navy. NASA/GSFC then process this data under the NASA Pathfinder Polar Data Set Generation Project, a continuation of a 15-year effort to make precise, consistent ice sheet elevation and surface characteristic data sets easily accessible to all scientific investigators. The "NASA Polar Ice Sheet Satellite Radar Altimetry Project" has maintained an on-line data base of level 1 (altimetry return waveforms) and level 2 (height elevations) and created higher order gridded products of all polar-ice radar altimetry data available including: SEASAT, GEOSAT & GFO, ERS -1 & -2, and TOPEX. The GFO data is extremely important in studying surface changes because of the similarity in altimeter design and orbit dynamics to the SEASAT and GEOSAT data.

--- return to Payload Calibration and Validation page ---

Radiometer/Radiosonde Comparisons

Computer Sciences Corporation (CSC) is monitoring the quality of the wet tropospheric path delay (PD) retrieval generated from the GFO Water Vapor Radiometer (WVR) data by making inter-comparisons of the GFO path delay with measurements from a global network of radiosonde observations (RaObs) of the atmosphere. Routine twice-daily RaOb launches are provided by the national weather service of a large number of participating countries around the world. Many of these launch sites are on small isolated islands, far from any significant land masses, and a number of these islands lie on or very near a GFO ground track. Overpasses by GFO within 300 km of such a site, and which occur within 360 min of a RaOb launch, are used as an inter-comparison point. The atmospheric profiles of temperature, pressure, and water vapor which are measured by the RaOb are used to perform a numerical calculation of integrated refractivity through the troposphere. The result is an independent, direct measurement for comparison with the WVR Path Delay retrieval.

--- return to Payload Calibration and Validation page ---

v

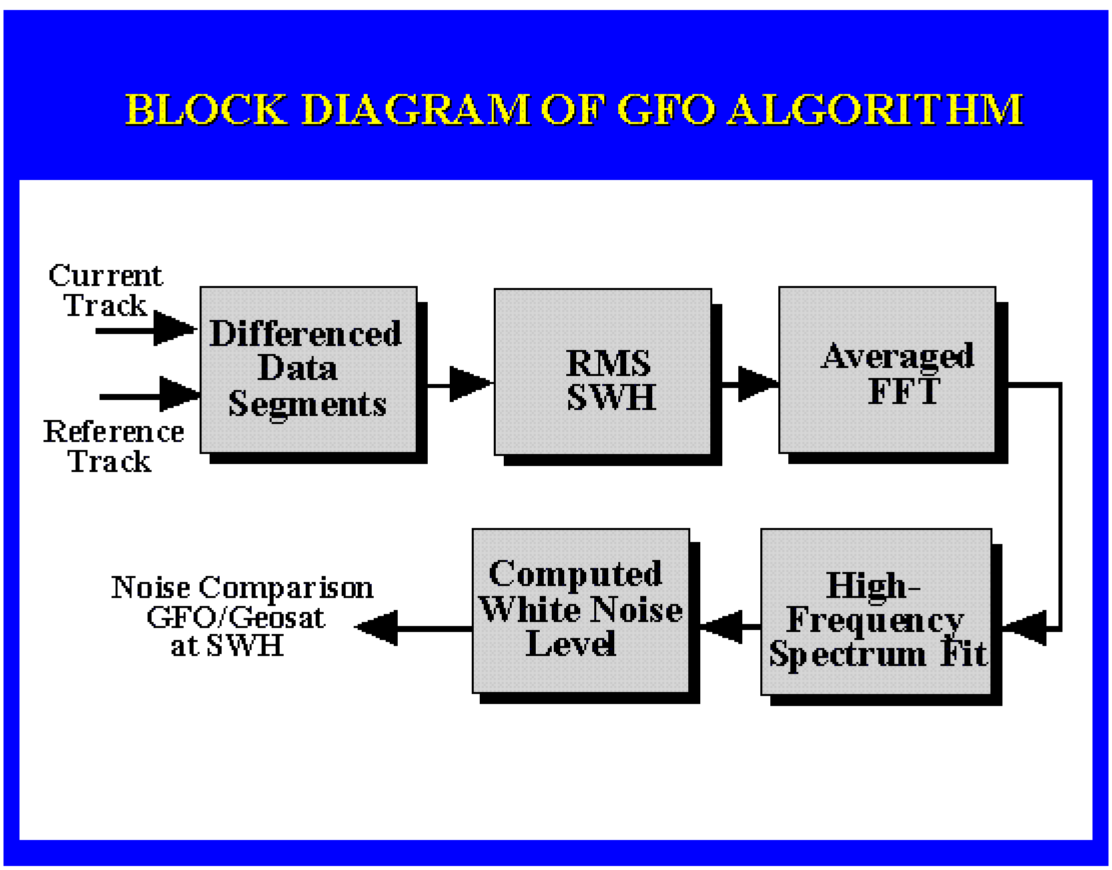
VALIDATION OF THE RADAR ALTIMETER PRECISION

As part of the validation of the quality of data from the GEOSAT Follow-On mission, the white noise level in the radar altimeter height data is monitored throughout the mission. The Cal/Val team obtains the GFO NGDRs from the ADFC at NAVOCEANO and from that computes the altimeter white noise precision. The white noise level in the altimeter data is important because it quantifies the precision limit of the altimeter height measurement and determines the minimum resolvable wavelength of the gravity field. The white noise level therefore forms the basis for the GFO technical specification.

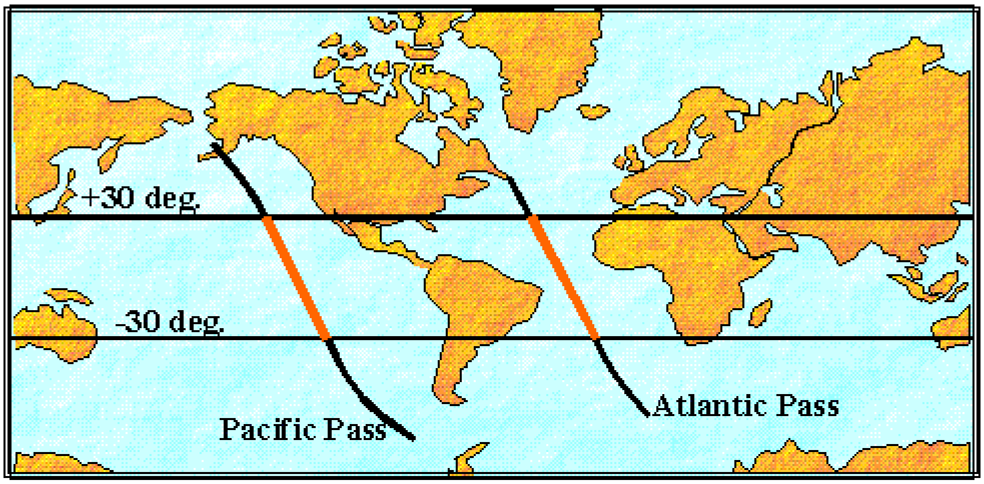
The white noise level is determined by differencing two repeat tracks to cancel out the geoid and other correlated signals. Then, spectral analysis reveals the "white noise floor" at high frequencies. This spectral technique for determining white noise level is applied to the Navy Geophysical Data Records (NGDRs) available from NAVO at a 1-Hz sampling rate. The technique used is identical to the technique used for the original GEOSAT Mission and results in measurements at the centimeter level. The Cal/Val team monitors the Radar Altimeter precision for each 17-day cycle of GFO operation.

The following sections describe the operation of the repeat track technique. Test cases were taken from the NOAA GEOSAT T2 GDRs with test data sets over a range of SWH show results consistent with the published results, establishing confidence in the new implementation.

ALGORITHM PROCESSING FLOW



Difference Data Segment: Ascending tracks between -30 deg. and +30 deg. latitude and with longitude near the tracks shown on the following plot were selected. GEOSAT data has shown that these regions reliably produce long continuous tracks over deep water for every day of the 17 day cycle. The difference track is constructed by subtracting closest points. The first 512 point segment with no data gaps is selected. If necessary in high SWH cases, a small number of wild points (>5 sigma) are removed.



RMS SWH: The SWH for each point on the Difference track segment is assigned as the maximum of the Reference or Current track point SWH. The RMS SWH for the segment is calculated to allow comparisons of the noise levels vs SWH. For GFO, the noise level specification goal applies for SWH less than 2 meters.

Averaged FFT: The long data segment (512 points) over-resolves the spectrum tail in the frequency domain, allowing eight 64 point transforms to be calculated, and the corresponding PSDs averaged, thereby reducing the variance in the estimate of the PSD tail. The PSD of the altimeter noise process is defined as one-half the PSD of the difference process. The FFT algorithm used is a realization of the Cooley-Tukey technique.

High-Frequency Spectrum Fit: The six points at the highest frequency bins of the noise PSD defined above are averaged to determine the high-frequency PSD level of the noise. This defines a "white noise floor" which appears as the high frequency tail of the noise spectrum.

White Noise Level Calculation: The altimeter RMS noise level at the SWH noted above is determined by integrating (over the folding frequency bandwidth, 0.5 Hz) to determine the total white noise floor.

Buoy/GFO Wind Speed and SWH Comparisons

Computer Sciences Corporation is monitoring the quality of the NGDR significant wave height and wind speed retrieval by the GFO radar altimeter by making comparisons of the GFO data with measurements from the NOAA Data Buoy Network.

--- return to Payload Calibration and Validation page ---

GFO Laser Orbits

NASA/GSFC is producing laser orbits for GFO that are on-line and can be downloaded from GFO Data.
A Summary of his orbit results and an Orbit File Format can be found in the same ftp directory.

--- return to Payload Calibration and Validation page ---

Water Vapor Radiometer Precision

Computer Sciences Corporation (CSC) is monitoring the Water Vapor Radiometer precision for each 17-day cycle of GFO operation. They use the GFO NGDRs generated by the ADFC at NAVOCEANO and provides an on-line file containing the necessary fields for computing the radiometer white noise precision.

--- return to Payload Calibration and Validation page ---

The Real Time Ocean Environment

The NRL-Stennis GFO data validation activity results are presented on the Real Time Ocean Environment home page.

A global map allows regional access to GFO, TOPEX and ERS-2 altimetry products and derived sea surface products. Information provided includes:

- Data sources: Information about the different altimeters from which the altimetry data is gathered.
- Data processing: Informaton on how the raw altimetry data is prepared and processed.
- Altimeter intercomparisons: Intercomparisons between processed altimetry data from the different altimeters.
- Altimetry Plots: Real time altimetry products and derived products, including sea surface height, sea surface height anomaly, significant wave height, wind speed, and sea surface temperature, presented globally and regionally. An archive of older images is also available for each region.
- Related sites and references: Links to other sites related to altimetry and oceanography.

--- return to Payload Calibration and Validation page ---

GFO Precision Orbit Determination Comparisons

Accurate orbit determination is crucial to maximize the yield of operational environmental data and of ocean science data from the GEOSAT Follow-On mission. Orbit determination accuracy directly affects the accuracy of the sea level measurements produced by the GFO system because the sea level measurements are generated by combining radar altimetry and orbit determination. Radial orbit error maps directly into sea level height error.

The original plan was to use data from the on-board GPS units to generate Precision Orbit Data (POD) for GFO. Without that data, the Navy and NASA cooperated and switched the POD to the use of laser orbit data generated by NASA/GSFC. The Navy receives fast look data within about 48 hours and uses that data to generate the gfoM NGDRs for its internal use (and also makes these, as well as the gfoO or operational data generated using the Doppler orbit data available to NASA and NOAA). NOAA receives more accurate smoothed laser orbit data and, as such data is available, uses that data to generate the NOAA IGDRs. The Cal/Val team uses NOAA generated data for verification/validation of the GFO satellite orbit accuracy and ensures data accuracy by comparing the the NOAA IGDRs with the NGDRs.

--- return to Payload Calibration and Validation page ---

Geophysical Algorithm Validation

This page provides documentation for the geophysical algorithms used to produce the NAVO NGDR:

- Geoid
  - Geoid height above the reference) ellipsoid.
  - Based on *Rapp and Pavlis* (1990). To apply this correction, it should be subtracted from the altimeter sea height, H.
  - Value computed with bilinear interpolation using 1-degree geoid height estimates.
- Solid Earth Tide (is this included as part of the FES95.1 correction below)
  - This is the Solid earth tide correction to H.
- Ocean Tide
  - Surface ocean tide correction to H is based on the FES95.1-Grenoble model. To apply this correction, it should be subtracted from the altimeter sea height, H.
- Dry Troposphere
  - Dry troposphere correction to H. This correction compensated for the rise and fall in ocean height due to changes in barometric pressure. It is based on the Navy NOGAPS model. To apply this correction, it should be subtracted from the altimeter sea height, H.
  - Surface values of air temperature and water pressure are computed along the satellite ground track and the correction to H is determined using the Topex algorithm.
- Wet Troposphere
  - Wet troposphere path delay correction to H. The amplitude of the water vapor correction varies from about 35 cm in the tropics to near zero near the poles. It is based on the GFO Water Vapor Radiometer measurements. To apply this correction, it should be subtracted from the altimeter sea height, H.
  - Computed at 1-second intervals using the Ruf algorithm cf. radiometer-radiosonde comparisons.
- Ionosphere
  - Ionosphere correction to altimeter surface height. This correction compensates for the altimeter travel time delay caused by the free electrons in the ionosphere. It is based on the JPL Global Ionospheric Model (GIM). To apply this correction, it should be subtracted from the altimeter sea height, H after the delta heights are determined.
- Orbit
  - Satellite height above the reference ellipsoid which is derived from both the Doppler orbit and the Medium Laser orbit produced at NAVSOC. The orbit height should be subtracted from the altimeter height, H. (Cf.: Laser array orbit determination at NASA).
- Altimeter Calibration
  - A drift in the altimeter height (possibly representing a steady degradation in the circuitry in the altimeter) was observed in the original GEOSAT-A altimeter appearing as a slow downward trend in the calibration corresponding to approximately 0.2 cm per year.
    A nearly constant drift in the GEOSAT-A spacecraft clock of about 3 parts per billion per year (equivalent to approximately 0.2 cm per year) was also found.
  - Initial estimate of GFO calibration constants can be found on the SDR format page under table of altimeter constants.
- Time Tag Error
  - Accurate time tags are fundamental to altimetry because the rapid rate of change of the satellite height relative to the sea surface. The Earth's oblate shape combined wit a slightly eccentric orbit can produce relative height rates as large as 20 m/s. A constant timing error of 1 ms can create height uncertainties as large as 2 cm. But such a timing bias can be determined from altimetry itself because of its characteristic twice-per-revolution signature in the data. A 79 ms timing bias initially contained in the Seasat altimeter data was verified (*Marsh and Williamson (1982)* and *Schutz et al. (1982)*) and a significantly smaller bias of 5 ± 3 ms was verified for the GEOSAT ERM (*Shum et al. (1990)*).

References

Rapp, R.H. and N.K. Pavlis (1990: The development and analysis of geopotential coefficient models to shperical harmonic degree 360. *J. Geophys. Res.*, *95* (B3), 21889-21911.

MacArthur, J.L., Marsh, P.C. and J.G. Wall, 1987: The Geosat radar altimeter, *JHU APL Technical Digest*, *8* (2), 176-181.

Marsh, J.G. and R.G. Williamson, 1982: Seasat altimeter timing bias estimatation, *J. Geophys. Res.*, *87* (C5), 3232-3238.

Schutz, B.E., B.D. Tapley and C.-K. Shum, 1982: Evaluation of the Seasat altimeter time tag bias, *J. Geophys. Res. 87* (C5) 3239-3246.

--- return to Payload Calibration and Validation page ---