From BlackJack To GOX:
The Transfer, Test, and Validation of the ROCSat-3 GPS Occultation Receiver

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Abstract:
ROCSat-3's primary instrument is the GPS Occultation Receiver (GOX) and is based on the Jet Propulsion Laboratory's (JPL) proven BlackJack GPS Receiver. The COSMIC GOX receivers will demonstrate an important new operational data type for near-real-time assimilation into weather models by providing over 2500 atmospheric profiles per day with a global distribution. All space-based GPS Occultation data to date has been produced by JPL receivers with the bulk of that data coming from the CHAMP and SAC-C missions. In order to capitalize on that successful heritage, NSPO and the University Corporation for Atmospheric Research (UCAR) have endeavored to adapt the CHAMP design for use on the ROCSat-3/COSMIC mission. JPL, sponsored by the National Aeronautics and Space Administration (NASA) via an agreement with the National Science Foundation (NSF), has partnered with UCAR and their sub-contractor, Broad Reach Engineering (BRE) to transfer JPL's BlackJack hardware design to BRE, assist in the manufacture, and validate the final product in support of this important mission.

As JPL completes the effort to validate all of the GOX flight units, it is an appropriate time to present a review of the development, manufacture, and validation of the mission hardware. This presentation will also discuss results from the testing sequences, comparing GOX data quality to CHAMP and SAC-C (the current standards of data quality). Finally, enhancements of the GOX onboard software will be discussed to the extent possible.

1. Introduction

The ROCSat-3/COSMIC mission of obtaining a large quantity of daily, global atmospheric limb-sounding readings depends on technology developed in the 1990's at the Jet Propulsion Laboratory (JPL). This limb-sounding technology is rooted in JPL's BlackJack GPS receiver architecture which is a direct descendent of the TurboRogue architecture employed on GPS/Met in 1995 and which is currently in use on the CHAMP and SAC-C missions currently providing several-hundred soundings per day. The COSMIC technology is an extension of the CHAMP technology with some key improvements incorporated to enhance the COSMIC data set.

In an agreement between the National Aeronautics and Space Administration (NASA) and the National Science Foundation (NSF), NASA agreed to funding JPL's participation in the ROCSat-3/COSMIC mission in exchange for near real-time access to raw COSMIC limb-sounding data. JPL's participation on behalf of NASA takes on a unique (for JPL) form where JPL has no direct delivery responsibilities for the entire GPS system (antenna, cables, receivers, etc…). Instead, JPL is acting in a supporting role to the University Corporation for Atmospheric Research (UCAR) development team (including their sub-contractors) in providing the basic technology, instrument design, on-demand consulting, and improved software capabilities for the limb-sounding experiment.

JPL's roles on ROCSat-3/COSMIC can be further defined as follows:

1) Design Transfer of the CHAMP Hardware,
2) Hardware and System Products Validation, and
3) Implementation of COSMIC-specific Software Enhancements.

JPL's roles and responsibilities associated with COSMIC are varied and wide-ranging and include many tasks not mentioned above. The tasking agreement between JPL and NASA includes over twelve major scope areas ensuring that JPL is indeed an integrated part of the COSMIC GPS receiver development and delivery. JPL has accomplished this task by establishing a consistent project management structure which pulls necessary talent from the existing GPS development organizations at JPL including the foremost experts in GPS receiver development and testing, RF electronics and antenna design, receiver sounding software, and sounding retrieval processing. In the last area, sounding retrieval processing, JPL and UCAR have established a close working relationship and exchange of ideas across the institutions to provide COSMIC with the best possible performance at launch.

2. Methods

In the role of Design Transfer, the CHAMP hardware design was licensed and transferred to UCAR's sub-contractor, Broad Reach Engineering (BRE). In the course of this transfer, JPL delivered drawings of the CHAMP design, advised BRE on the necessary modifications to the design required for COSMIC, provided systems engineering support for BRE with respect to the entire GPS system on the Spacecraft, and interacted with the BRE design team at a very low level to ensure an accurate performance replication of the CHAMP receiver. JPL also re-designed and improved one of the key clock circuits in the CHAMP design to mitigate the effects of the 1Hz "ringing" of the primary receiver oscillator that can be observed in the CHAMP and SAC-C occultation data. JPL participated in every step of the hardware redesign and manufacturing process at all levels of design detail.

Design drawings licensed to BRE were modified by BRE and then validated by JPL. BRE re-packaged the CHAMP design making both dramatic and subtle improvements in the design to enhance manufacturability, testability, and longevity. Where appropriate, BRE replaced commercial components to establish a more reliable parts baseline enhancing the overall lifetime of the receiver hardware. Each design change was evaluated by JPL and then discussions were held at the lowest levels offering BRE a rigorous peer-review of the final hardware design. The final step in the validation process for the hardware design involved formal reviews by UCAR, JPL, and Orbital. By implementing this peer-level and formal review process, the CHAMP design was advanced resulting in a more robust receiver where performance was not degraded by the repackaging effort.

JPL, in collaboration with BRE, redesigned the RF section, sampling down-converter, and reference oscillator circuits to remove the well-documented "1Hz" variations in clock performance affecting sounding retrievals. The first step in this process was to “clean-up” the overall RF design and to isolate RF components in separate chambers within the receiver mechanical construction. A careful re-layout of the sampling down-converter and the addition of some power-isolation circuits reduced the cross-channel signal interference and further isolated the reference oscillator from the sampling circuits. Finally, a detailed study of the reference oscillator itself including consultations with the oscillator manufacturer resulted in an oscillator characterization program where serialized components were screened by JPL for improved oscillator performance. The summation of these activities has resulted in a receiver with greatly reduced 1Hz frequency variations and will improve the overall retrieval accuracy.

In the role of Hardware and System Products Validation, JPL has developed a suite of test configurations, procedures, and specialized ground equipment to validate the receivers as built by BRE. This validation goes beyond the normal, workmanship validation that BRE performs as a normal course of the manufacture of the hardware. It encompasses several configurations to assess the performance of the hardware in various, flight-similar scenarios and continues the type of pre-launch validation that JPL performs on all GPS receivers built in-house. By validating the final hardware products, JPL and ensure that all necessary characterizations of the flight hardware have been performed and that on-orbit performance is optimized.

The test configurations employed by JPL for the flight hardware include:

1) a basic hardware acceptance test,
2) an RF channel-to-channel leakage test,
3) a passive antenna (noise figure) characterization,
4) a thermal cycle performance characterization,
5) a long-duration acquisition and tracking characterization, and
6) a zero-baseline (comparison) test.

In addition, over 2000 hours of operating time is put on each flight unit to screen components for infant mortality. These tests use both rooftop antennas and JPL custom-designed GPS constellation simulator that simulates on-orbit conditions with the exception of atmospheric conditions. Various special test fixtures and mounting simulators are also used to replicate conditions as accurately as possible.

In the basic hardware acceptance test, basic receiver functions including acquisition and tracking capability, reprogramming capability, telemetry checks, and other basic operational capabilities are evaluated with pass/fail criteria. Receiver-specific functions such as clock steering are also evaluated on a pass/fail basis. One of the most important tests for a science instrument such as this is the test of the capability to safely update the operating software on the receiver through spacecraft interfaces. This ensures that improvements in tracking and signal processing gained from on-orbit experience can be realized in the on-orbit receiver rather than waiting for the next generation receiver development. The suit of hardware acceptance tests ensures that the receiver functions to a basic level of performance and is a gate for the subsequent tests and characterizations.

The RF Channel-to-Channel Leakage Test is used to assess the independence of each of the four RF channels of the receiver. Each channel is attached to a separate antenna and during normal operations all channels are active. By establishing that the channels do not suffer from excessive crosstalk, the RF front-end is further validated in a flight-like configuration.

The Passive Antenna Characterization allows JPL to characterize the overall sensitivity of the receiver to establish it's ability to track occultation events below 1 km.

The Thermal Cycle Performance Characterization allows an evaluation of the changes in receiver performance over the expected operating temperature range. More time is spent in the cold range on this characterization reflecting the expected cold thermal environment of the ROCSat-3/COSMIC mission.

The Long-Duration Acquisition and Tracking Characterization provides a long-term data set to look for rarely occurring anomalies in the performance of the hardware.

Finally, the Zero-Baseline Test is a comparison between the receiver under test and a reference receiver showing that the data from the ensemble of receivers can be combined with little receiver-specific error added.

The final role that JPL fills for COSMIC is that of software developer for the receiver. With the experience of the SAC-C and CHAMP receivers fresh in the minds of the science team for COSMIC, several improvements and additional capabilities were added to the COSMIC receivers. JPL retains the intellectual property associated with the receiver including the software and therefore was tasked to make the requisite changes to the software for COSMIC. These changes primarily include the addition of three capabilities:

1) the simultaneous recording of multiple (up to 3) soundings,
2) the ability to transition from closed-loop to open-loop, atmospheric model driven tracking in parameter-driven situations, and
3) the ability to track soundings associated with "rising" GPS vehicles where the ray-path moves from lower altitudes to higher altitudes.

These new capabilities are independent of the hardware implementation and are implemented by testing new algorithms on the SAC-C spacecraft. This method of developing the new capability and uploading it to an existing, orbiting spacecraft is a very valuable tool in establishing the performance of the new capabilities prior to COSMIC launch. In addition, it enables the science team to "preview" the new data before the COSMIC launch and it enables the CDAAC to "practice" data handling and processing using real-world data. NASA as a part of the tasking agreement for COSMIC also provided the use of the SAC-C instrument COSMIC.

Unfortunately, further discussion of the improved software capabilities cannot be released due to International Trade in Arms Restrictions (ITAR) considerations.

3. Results and Discussion

At the time of the preparation of this document, JPL has completed the Design Transfer activities, is actively performing both the Hardware Validation and Software Development activities. The Design Transfer activity progressed smoothly and the both the Hardware Validation and the Software Development activities are progressing with the "normal" hiccups and delays, but are both making significant progress towards meeting the ROCSat-3/COSMIC goals. In these efforts, priorities are placed on the Hardware Validation efforts as this allows for the approval and delivery of the actual flight units to the spacecraft integrator. Since the software will be updated after ATLO and prior to launch, the software development schedule is more flexible.

JPL has fully evaluated two flight units and has two more under evaluation at this time. The remaining two flight units are anticipated to arrive at JPL in mid-April, 2004 and all testing will be completed by the end of May 2004.

Flight Unit #1 was evaluated by JPL and delivered to Orbital for spacecraft integration in December 2003. After passing its initial acceptance tests, the characterization sequences progressed smoothly from one stage to the next. This unit took three months to assess in order to provide the necessary time to optimize the testing procedures and documentation. After evaluating this unit, it has been deemed acceptable for flight and has been integrated onto the first spacecraft currently undergoing qualification testing.

Flight Unit #2 was evaluated by JPL and delivered to Orbital for shipment to NSPO in April 2004. Like unit #1, the testing progress smoothly but at a more rapid pace due to the experience of the test team and the streamlining of the procedures.

Flight Unit #3 is in mid evaluation and will be completed at the end of April.

Flight Unit #4 failed its initial acceptance test and after a weeklong period of debugging was returned to BRE for the replacement of the reference oscillator. This unit will be re-evaluated after it has been re-worked.

Flight Unit #5 is in the beginning stages of evaluation and will be completed at the end of May 2004.

Flight Unit #6 has not yet been received for evaluation.

During the testing of the flight electronics units, JPL also tested the flight antenna units. This testing was done in a remote location with our custom COSMIC spacecraft simulator. During this testing, the limb sounding antenna demonstrated some rather abnormal behavior and further testing at JPL confirmed that the antenna, when coupled to the spacecraft, did not perform as expected or in a suitable fashion. JPL and UCAR then established a "tiger-team" of JPL antenna experts, JPL GPS experts, and the antenna manufacturer, Haig-Farr, Inc. to investigate the anomalous behavior. After some subsequent testing and evaluation, it was determined that a particular RF mode at the GPS-L2 frequency (1227 MHz) was being excited by the spacecraft ground plane and canceling the GPS-L2 signal. After further evaluation and testing, a "skirt" modification to the antenna was developed to remove the mode and to restore the antenna to it's expected performance.

Also during the testing of the flight electronics units, extensive compatibility testing of the GPS receiver and another COSMIC instrument, the Tri-Band Beacon (TBB) was performed on our spacecraft simulator and on an Engineering Model of the spacecraft. These compatibility tests showed an effect on the GPS performance in certain conditions of the TBB operation. Further characterization and testing is underway with the TBB, however, mitigation strategies for this issue are limited.

The software development activities continue to progress at a steady pace with the first capability, the simultaneous recording of multiple (up to 3) soundings, being completed and tested on-orbit with the SAC-C spacecraft. The current implementation on the SAC-C spacecraft is limited to "setting" soundings pending the further development of the rising occultation capability. The second capability, the ability to transition from closed-loop to open loop, atmospheric model driven tracking in parameter-driven situations is in development with refinements of the atmospheric model continuing as the transition software is matured. Current results from that capability are also beginning to be available from the on-orbit testing using the SAC-C spacecraft. The final capability, the ability to track soundings associated with "rising" GPS vehicles where the ray-path moves from lower altitudes to higher altitudes, is still in the early stages of development with an expected summer 2004 completion date.

4. Summary

JPL's tasks associated with the ROCSat-3/COSMIC mission are broad-ranging and will help to ensure the successful collection of atmospheric (neutral and iono) limb soundings using the GPS techniques demonstrated on GPS/Met, CHAMP, and SAC-C. JPL's low-level involvement with the design and construction of the flight hardware has ensured that the hardware will be capable of performing to the high standards set by CHAMP and to exceed them in some aspects. JPL's testing and validation sequences will provide the community with the "expert opinion" of the performance of the essential flight hardware capabilities. Finally, as the primary software developer for all flown GPS Limb Sounding instruments to date, JPL's contribution to the ROCSat-3/COSMIC software development will ensure that this instrument is the state of the art for limb sounding at launch.