Observed GPS Signal Continuity Interruptions

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ABSTRACT

During an autoland flight test of Stanford's Integrity Beacon Landing System in October 1994, one approach was aborted before landing due to a temporary satellite outage. Analysis showed that both the aircraft and ground reference GPS receivers lost lock on one satellite for six seconds. In subsequent weeks, we observed similar outages on most of the Block II satellites. Analysis of this data did not indicate a cause for these outages.

According to the satellite operators, this is a generic spacecraft problem. Command uplinks to Block II (but not IIA) satellites occasionally cause a conflict in the spacecraft computer. A conflict causes the spacecraft to emit a non-standard PRN code during one navigation data subframe (six seconds). These conflicts occur roughly 0.3 times per satellite per day. A simple Monte Carlo analysis shows that, in the worst case, this phenomenon could reduce availability of GPS precision landing systems by a factor of ten.

This type of outage is not described in the standard literature on GPS spacecraft reliability, nor is it monitored by the FAA's Performance Analysis Network (PAN). The FAA has recently contracted to upgrade PAN to continuously monitor spacecraft signals. As a result, accurate data on spacecraft signal continuity will soon be available to researchers.

THE QUESTION

During October 1994, Stanford University conducted a flight test of its Integrity Beacon Landing System (IBLS). Conducted in cooperation with United Airlines and the Federal Aviation Administration (FAA), the test involved navigating a Boeing 737 airliner down a precision approach to a fully automatic landing. The object of the test was to confirm that GPS-based systems are capable of providing the navigation accuracy and integrity needed to land aircraft even in the worst weather conditions.

The test was a complete success, resulting in 110 successful automatic landings [1]. One landing approach was aborted due to a brief loss of signal from one GPS satellite, as described below. That one abort attracted our interest because it spoiled an otherwise perfect record. We carried out an extensive postflight analysis to trace the cause of this signal loss.

At the time, the IBLS system used a six-channel GPS receiver. Two channels are required to track the Integrity Beacon pseudolites on the ground, leaving only the necessary minimum of four channels to track GPS satellites. If the receiver lost lock on even one satellite, the system would be required to abort the approach. (The current version of IBLS uses a nine-channel GPS receiver and would not cause an abort in this situation.) To avoid this possibility, we carefully selected a set of healthy high-elevation satellites before each approach.

Our postflight analysis showed that both our airborne and ground reference receivers had simultaneously lost lock on spacecraft (PRN) 17. Six seconds later, both receivers simultaneously regained lock on the signal from that spacecraft. No other satellite signals were affected on either receiver. We performed tests for several days at the same sidereal time (constellation configuration) and this phenomenon did not recur. This made us suspect a one-time satellite signal failure, as our alternative explanations (a common receiver failure mode or a precise burst of interference) seemed highly improbable.

The Navigation Information Service (NIS) operated by the US Coast Guard is the designated point of contact for civilian questions about the GPS system. We called the NIS, explained the situation to the watchstander, and asked whether anything had happened to PRN 17 at the instant we lost its signal.

The Coast Guard watchstander called the 2nd Space Operations Squadron (2SOS) at Falcon Air Force Base, Colorado. 2SOS controls the satellite constellation, but only military users can contact them directly. The watchstander reported back to us that 2SOS had been sending commands to that spacecraft at the time the glitch occurred and that 2SOS had also seen the glitch. The watchstander added that 2SOS had given him the impression that such glitches were not uncommon, although he himself had never heard of them before.

Unable to get a better explanation, we fell back on our own resources. We set up a GPS receiver in our lab to monitor the constellation continuously and report any glitches. We duplicated the experiment in another lab using a different receiver with a different internal architecture, to eliminate the possibility that we were seeing some kind of internal receiver error. After two weeks of taking data, we had observed a total of eleven glitches similar to the one which caused our landing abort. Each glitch occurred simultaneously on both receivers. The only common thread we could detect was that we observed glitches on Block II spacecraft only, not on Block I or on Block IIA.

As we collected and analyzed the data, it became clear that we had discovered some sort of generic spacecraft problem which was not reflected in the literature on spacecraft failure modes and failure rates. This presented us with a dilemma. Members of our group were analyzing the ability of various air navigation system designs to meet specified Required Navigation Performance (RNP) parameters, including system availability and continuity. The analysis was based on the published failure models, but we now had data showing that those models were incomplete.

To resolve this dilemma, we decided to contact 2SOS directly. We outlined our observations, our concerns, and our need for accurate failure models in a letter requesting a better description of this phenomenon. To their credit, 2SOS responded very quickly with a full explanation.

THE ANSWER

Each GPS spacecraft continually broadcasts its own ephemeris and other data to user receivers. Current spacecraft are not capable of generating this data on their own. Instead, the data is read in realtime from a buffer memory on board the spacecraft, which the satellite operators must periodically refill with new data. This refilling process is called a "navigation data upload." Each satellite is refilled about once a day, on the average. Due to the amount of data involved, each upload takes about ten minutes to complete.

During the upload, one part of the spacecraft computer program is writing to the buffer memory, while another part of the program is reading broadcast information from that same memory. On the Block II spacecraft, it seems that these two processes occasionally conflict, and the broadcast data for one navigation data subframe does not reach the navigation signal transmitter in time. The transmitter shifts to a *non-standard C/A code* for the duration of that subframe, as it is designed to do whenever its broadcast data is invalid. This non-standard C/A code is intended to be "invisible" to user receivers; the receiver sees this event as a loss of signal from that satellite. The loss of signal lasts for one subframe, or six seconds.

The characteristics of the glitch we saw match this explanation perfectly. Unfortunately, the precise cause of this conflict is unknown, and there appears to be no feasible workaround to prevent it. It does not happen during every upload. Statistics collected by 2SOS show that the frequency of occurrence is roughly 0.3 glitches per spacecraft per day. Because the current constellation contains nine Block II spacecraft, we would expect to see about three glitches per day in the constellation. (According to 2SOS, a similar glitch was seen one time on one Block IIA satellite. Future satellites are not expected to exhibit this problem.)

The glitches are not uniformly distributed. According to 2SOS, most uploads are performed during the second shift (2200 to 0600 UTC) to satellites in view of the control station in Colorado. This is done for reasons of operational convenience rather than necessity, however, and the procedure may change at any time.

THE IMPACT

Of all GPS applications, precision landing is perhaps the one which can least easily tolerate short signal outages. Most applications can "ride out" a six-second navigation outage. However, precision landing systems are required to annunciate a navigation failure within one or two seconds, and automatic landing systems must abort the approach after a navigation failure.

To gauge the impact of this satellite signal failure mode on our ongoing analyses, we performed a simple Monte Carlo study of landing system availability with and without this glitch. For 20,000 random trials, the study considered whether at least four satellites (the minimum required for navigation) were visible above a 7.5 degree elevation mask angle at one of nine Category III airports worldwide. Because a precision landing system could not tolerate the Block II uplink glitch with only four satellites available, we flagged those cases for separate treatment. The study introduced spacecraft failures at appropriate rates using the satellite availability model published by Phlong and Elrod [2].

The study showed that the availability of GPS for precision landing, without considering the Block II uplink glitch, was 99.965 percent. Removing the cases where only four satellites were available, and at least one of them was a Block II satellite, the availability of GPS navigation fell to 99.34 percent, over ten times worse. This difference illustrates the impact that incomplete spacecraft failure models can have on system analyses.

This study shows a *relative* difference between two sets of assumptions, but it should not be considered as a guide to *absolute* levels of GPS availability. The study considered a relatively small number of cases, and it did not address augmentation methods such as pseudolites or geostationary satellites. Nevertheless, it does show the need for more accurate models.

THE IMPLICATIONS

The discovery of these glitches was a surprise to us and to most of our fellow researchers. The second surprise was that the glitches were *no* surprise to the satellites' builders and operators. Every time a spacecraft shifts to non-standard code, it sends a message to the control center. This uplink glitch was even seen in prelaunch testing of the Block II spacecraft. Nevertheless, we have not seen it mentioned in the literature. No one tried to cover up the problem; rather, those who knew about it seemed to believe no one else would be interested.

We have illustrated above the importance to researchers of accurate models of spacecraft behavior. The fact that this glitch was unknown to the research community for so long begs an important question: Are there other spacecraft anomalies with similar impact which remain unknown today? If so, tomorrow's systems may not perform as well in the real world as today's analyses predict.

Fortunately, the Federal Aviation Administration (FAA) has just begun a program which will help answer that question. This is the Performance Analysis Network (PAN), which is operated under contract by Overlook Technologies. The PAN monitors the signals of the GPS constellation from three locations within the United States, and logs any deviations from the Standard Positioning Service specification. The PAN has actually been in operation since 1993, but the data collected to date has generally been too sparse to provide accurate signal continuity models [3].

Last spring, the FAA modified the PAN contract to support development of the Wide Area Augmentation System (WAAS). One of the new provisions requires the PAN to collect availability, continuity, and accuracy data at a once-per-second rate on all spacecraft in view of each monitor station. The PAN will not begin operating in this mode until late 1995, and it will take some time after that to collect enough data to develop accurate statistics. However, it will not be too long before models of spacecraft performance based on actual data, rather than predictions, become available to the research community. This should help quell the fear that our spacecraft models may not reflect reality.

THE MESSAGE

The purpose of this paper is to document this particular satellite signal failure mode in the literature. Analysis of highly demanding navigation applications, such as precision landing, must incorporate all known failure modes and rates, else they may lead to inaccurate conclusions. The PAN is about to start collecting signal continuity data from actual experience. We expect that PAN data will serve as an accurate baseline for future analyses.

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DAVE's ORIGINAL ABSTRACT

ABSTRACT

In a recent experiment conducted at Stanford, GPS carrier phases were recorded at 1 second intervals for a period of two weeks, using two models of receivers. The experiment was motivated by an anomaly noticed during an autoland attempt using GPS. A high elevation satellite was simultaneously lost on the aircraft and at the reference station causing the autoland to be aborted. The purpose of this experiment was to look for similar unexpected interruptions in the GPS signals. Such interruptions will impact the availability and continuity of precision landing systems that use GPS.

The results show that short-term glitches are not uncommon on certain satellites. A high-elevation satellite was lost approximately once per day during the study. The outages typically lasted for less than fifteen seconds. This phenomenon was observed on six Block II satellites (PRN's 2, 14, 15, 16, 17, 20) and on both receivers. Further data is being collected. The results of this on-going study will be presented.