AMOS Galaxy 15 Satellite Observations and Analysis

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1 ABSTRACT

In early April 2010, the Galaxy 15 geosynchronous satellite experienced an on-orbit anomaly. Even though the satellite's transmitters and articulating solar panel were still functioning, ground controllers lost the ability to command and maneuver the satellite. With its orbital position no longer maintained, Galaxy 15 began to drift eastward. This forced several other satellites to make collision avoidance maneuvers during the following months. Soon after the initial anomaly, Galaxy 15's operators predicted that the satellite's reaction wheels would eventually become saturated, causing a loss of both spacecraft attitude and proper sunward orientation of the solar panels. This "off-pointing" event finally occurred in late December, ultimately leading to a depletion of Galaxy 15's batteries. This near-death experience had a fortunate side effect, however, in that it forced the satellite's command unit to reboot and once again be able to both receive and execute ground commands. The satellite operators have since recovered control of the satellite. AMOS conducted non-resolved photometric observations of Galaxy 15 before, during and after these events. Similar observations were conducted of Galaxy 12, the nearly-identical replacement satellite. This presentation presents and discusses these temporal brightness signatures in detail, comparing the changing patterns in the observations to the known sequence of events.

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2 INTRODUCTION

Intelsat's Galaxy 15 satellite was launched into geosynchronous (GEO) orbit on an Ariane 5G vehicle 2005 Oct 13 along with another satellite (Syracuse 3A). Orbital Corp. manufactured Galaxy 15, along with two nearly identical sister models, Galaxy 12 and 14 [1]. Figure 1 shows artist renderings of the three satellites which use Orbital's *Star-2*™ design, featuring a roughly cubical bus (measuring 1.75 m × 1.7 m × 1.8 m) and two solar panels (each measuring approximately 1.6 m × 4 m) extending on axels from the bus. For nominal operations, these Galaxy satellite buses typically maintain an Earth-facing attitude and the solar panels articulate about an axis aligned with Earth's N/S poles in order to maintain optimal sun-ward orientation. Each of the three sister satellites carries a payload of multiple C-band transponders to perform their commercial communications tasks. However, Galaxy 15 also possesses a series of L-band transmitters to broadcast GPS navigation data for the FAA's Geostationary Communications and Control Segment mission [1].

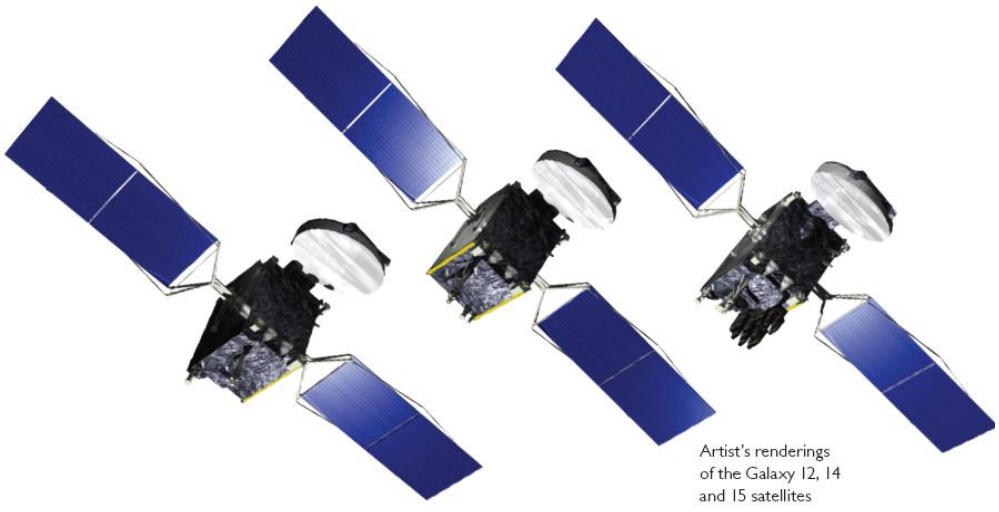

Figure 1 Artists renderings of Galaxy 12, 14 and 15 [1].

On 2010 Apr 05, Galaxy 15 lost the ability to receive and execute up-linked commands [2]. At that time, the satellite began to drift slowly through the GEO belt, because it could no longer perform occasional trajectory correction

maneuvers commanded from ground controllers required to maintain its preferred position at 133° W longitude. Notably, during this free-drift period, the satellite continued both L- and C-band transmissions, clearly indicating that its batteries were still fully charged, and that it was maintaining a proper bus attitude and sun-ward orientation of its solar panels. Thus, despite the inability to execute up-linked commands, the Galaxy 15 satellite continued functioning relatively normally, suggesting that its systems were basically intact and raising the hope that it could one day be recovered (which ultimately occurred several months later). During this free-drift period, the Galaxy 15 satellite was the subject of considerable attention because it posed a threat to other operating GEO satellites, either by physical collision or through electromagnetic interference from its L- and C-band transmitters. Figure 2 shows some examples of open-source media headlines concerning the Galaxy 15 during this period.

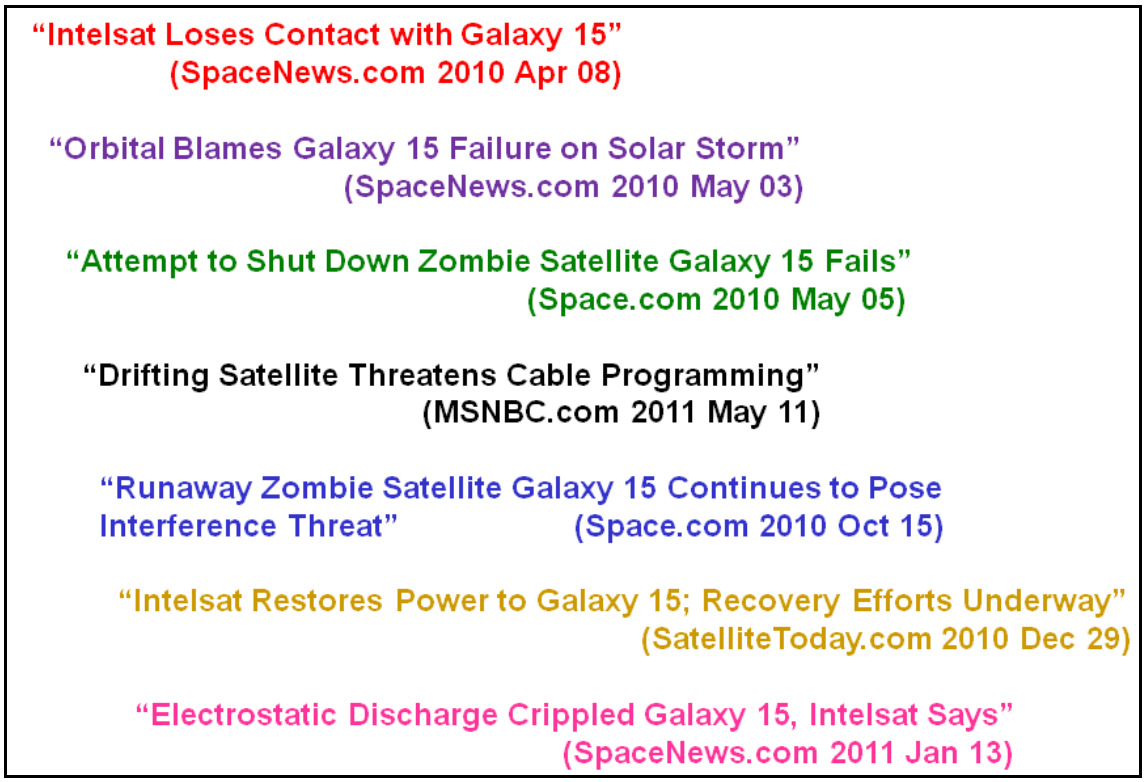

Figure 2 Example media headlines during the Galaxy 15 satellite anomaly.

Soon after the anomaly, Intelsat re-assigned, Galaxy 12, to perform the tasks normally assigned to its misbehaving sister satellite, and quickly re-positioning this nearly identical on-orbit spare to a position suitable for the task [2]. However, during the days and weeks immediately after the anomaly, Intelsat's engineers continued to try to regain control of the wayward Galaxy 15 satellite, and devoted considerable resources to analyzing the cause of the problem, and devising plans for corrective actions [2]. Within a few weeks, they determined more definitively that the satellite was indeed basically functioning nominally, despite its inability to execute up-linked commands. One result was that ground engineers could no longer instruct the satellite to maintain its GEO position. Perhaps more crucially, however, was that they also lost the ability to command the satellite to perform another critical function: execute maneuvers to reduce unwanted angular momentum from the attitude control system's reaction wheels [2]. In fact, several weeks after the anomaly, Intelsat announced that these wheels would eventually reach their limits and become saturated with momentum, an event they originally predicted to occur in late August or early September 2010, but later revised to between 28 November and 29 December 2010 [3, 4]. Their predictions also indicated that this wheel saturation would cause an "off-pointing" event — a loss of Earth-lock and overall satellite stability, with the solar panels no longer properly tracking the Sun. After that point in time, the satellite would become solely reliant on progressively discharging batteries. Notably, the engineers also concluded that this seemingly perilous event could provide an opportunity for full recovery of control, because when the batteries finally discharged to a critical level, the satellite would likely automatically re-boot critical onboard systems that would ultimately re-enable its ability to receive and execute commands.

Galaxy 15's reaction wheels did eventually saturate on 2010 Dec 17, leading to the predicted off-pointing event, and the eventual full recovery of the satellite [6]. Specifically, Intelsat officials report that Galaxy 15 lost Earth lock at 08:23 UT on Dec 17, promptly causing it to lose enough power to shut down its C- and L-band payloads [6, 7]. The satellite then likely began to rotate in a complex fashion (i.e., nutate) [7]. Six days later on Dec 23 the batteries drained to a sufficient level to cause the baseband command unit to reset automatically, allowing it to once again accept commands and permitting ground controllers to regain control and place the satellite in a safe mode [6, 7]. Since that time, the Galaxy 15 satellite has executed ground commands normally, and has been repositioned to a location close to its original, pre-anomaly GEO orbital slot [8].

3 OPTICAL OBSERVATIONS AND ANALYSIS

This paper presents optical observations of the Galaxy 15 satellite acquired before and during these events. The discussion focuses specifically on the ground-based temporal photometry, i.e., time-series brightness measurements of sunlight reflected from the entire satellite. The accompanying analysis seeks to show how these measurements can be interpreted to evaluate and/or confirm the status of the satellite, and thereby potentially used in anomaly resolution studies of similar future failures of GEO satellites. Table 1 summarizes the significant events for the Galaxy 15 satellite from launch, to the date of the anomaly, then through the free-drift period, and the final recovery phase. The first two columns of the table summarize the dates of significant events on the satellite, and the third column describes the associated optical observations important for satellite characterization and/or any potential anomaly resolution studies. Table 1 describes both photometric (brightness) as well as astrometric (positional) optical measurements.

Date(s)	Event(s)	Optical Observations
2005 Oct 13 to 2010 Apr 05	1. Deployed in GEO belt slot at 133° W 2. Stabilized main bus with sun-tracking solar panel	1. Positional measurements 2. Periodic baseline brightnesses measured in stabilized configuration
2010 Apr 05	1. Loss of command authority 2. Loss of navigational control	
2010 Apr 08 to Apr 13	1. Galaxy 12 replacement satellite maneuvered from 123° W to 133° W	1. Positional measurements 2. Eventual brightness measurements
2010 Apr 05 to 2010 Dec 17	1. Drifts eastward in GEO belt 2. Remains stabilized with good solar panel orientation	1. Positional measurements 2. Measured brightnesses confirm nominal attitude configuration
2010 Dec 17 08:23 UTC	1. Satellite losses Earth/Sun lock 2. Goes unstable with rotational motion	1. Brightness change detected 2. Brightness periodicity detected
2010 Dec 17 to 2010 Dec 23	1. Satellite continues rotational motion (batteries discharging)	1. Ongoing periodicity detected in brightnesses
2010 Dec 23	1. Discharged batteries cause sys. reboot 2. Command authority recovered	
2010 Dec 23 to Present	1. Navigated back to nearly original GEO slot 2. Satellite again stabilized with good solar panel orientation	1. Positional measurements 2. Measured brightnesses confirm nominal attitude configuration

Table 1 Significant Galaxy 15 satellite events

3.1 Astrometric Measurements

Figure 3 shows both the orbital longitude (left) and inclination (right) of the Galaxy 15 satellite before the anomaly, then as it drifted through the GEO belt, and then finally as ground-controllers maneuvered it back close to its post-anomaly location. The pink points on the plots show measured position values, derived from optical astrometry observations acquired from Maui and other optical sites. The earliest plotted times show the data before the anomaly and associated loss of control. This period is followed by the free-drift period, characterized by an increasing trend in both longitude and inclination. The blue curves in Figure 3 show free-drift orbital predictions propagated from a time shortly after loss of control, clearly indicating that the satellite had indeed discontinued any navigational maneuvers, and was not subject to any unknown forces affecting its motion.

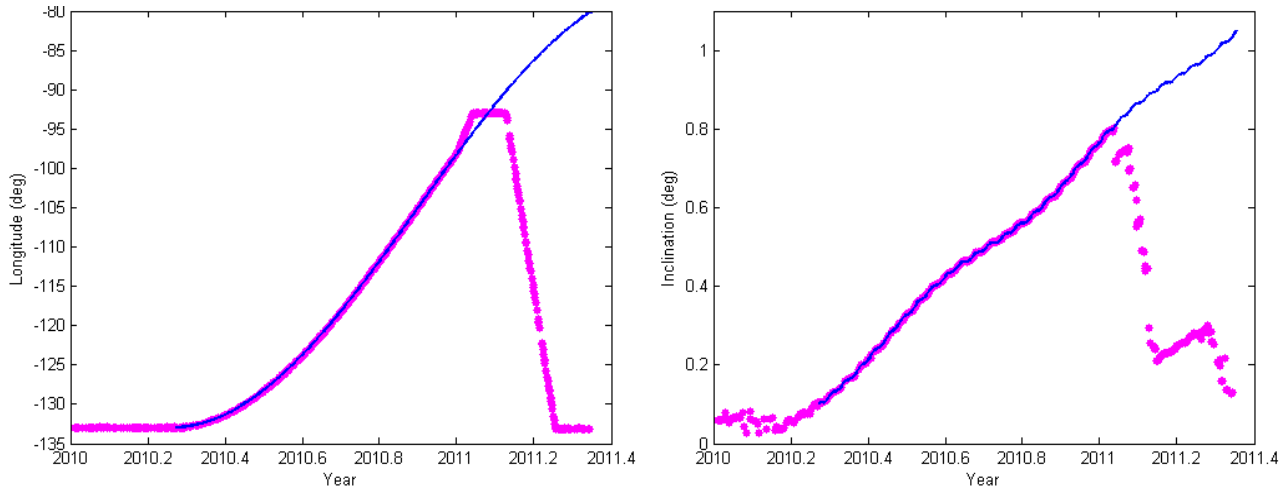

Figure 3 Galaxy 15 longitude and inclination vs. time.

3.2 Galaxy 15 Pre-Anomaly Photometric Measurements

The AMOS 3.6 m telescope acquired some limited temporal photometry of the Galaxy 15 satellite in its post-launch period, well before the anomaly. Figure 4 shows these measurements acquired during the period between 74 and 90 days after the 2005 Oct 13 launch (i.e., between 2005 day 360 and 2006 day 11). Note the color coding for observations acquired on different nights. The plot shows the brightness (measured in I-band stellar magnitudes normalized to a range of 40 Mm) as a function of UT time of day. Unfortunately, these observations were acquired in an opportunistic fashion, as part of a program to gather some representative satellite temporal photometry measurements. As such, the measurements were intermittent and somewhat sporadic, and do not provide overlapping coverage over multiple nights, much preferred for stabilized GEO satellites. However, even with this incomplete coverage, the composite signature has a mostly smooth appearance punctuated with some occasional, glint-like features of moderate amplitude (e.g., the feature plotted in green measured on 2005-360 near 11:50 UT and the feature plotted in black measured near 07:40 UT).

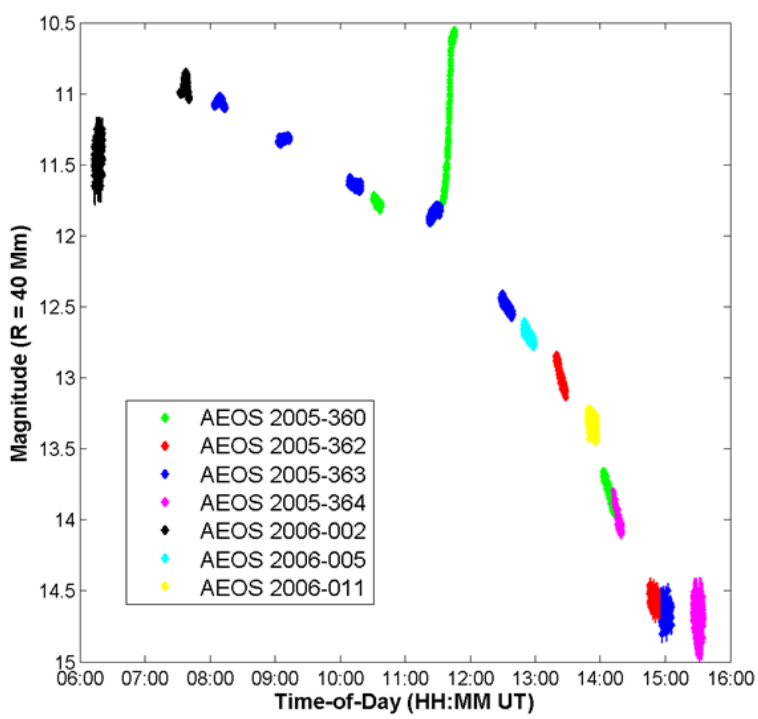

Figure 4 Galaxy 15 brightness measurements from the AMOS 3.6 m acquired just after launch.

3.3 Galaxy 12 Replacement Satellite Photometric Measurements

Because the pre-anomaly measurements of Galaxy 15 shown in Figure 4 provide only sporadic and limited time-of-day coverage, a focused observational study was conducted of its sister satellite, Galaxy 12. This study sought to use Galaxy 12 as a proxy object, in an effort to measure the baseline photometric behavior of the nearly-identical Galaxy 15 satellite. Figure 5 shows Galaxy 12 data acquired using a 0.4 m telescope at the AMOS Remote Maui Experiment (RME) site during six nearly consecutive nights. The observations were conducted after Galaxy 12 had been re-located to Galaxy 15's pre-anomaly position, and during a period of time when Galaxy 12 was known to be functioning normally in all respects. Because these measurements were acquired as part of a focused study, they provide overlapping coverage over multiple nights, and clearly indicate the consistent and largely repeatable nature of the brightness signatures. This consistency confirms that this satellite employs attitude stabilization and solar panel articulation modes commonly employed by many GEO communications satellites, which naturally produces such night-to-night repeatability. The signatures clearly show several of the same kind of occasional, glint-like features of moderate amplitude hinted at in Figure 4. However, the more comprehensive coverage of this data set indicates that while most these glints persist night after night over this several day period, as least some appear, disappear and/or change as the seasonal solar illumination slowly changes. For instance, on Figure 5 near 13:40 UT no glint feature was detected from RME on 2010 Nov 28 (red points), but was detected several days later for two days in a row, on Nov 04 and 05 (cyan and black points, respectively). This indicates that such stabilized GEO time-of-day signatures measured from a single ground-based site remain largely repeatable over periods of a few days, but not likely over periods significantly longer than that.

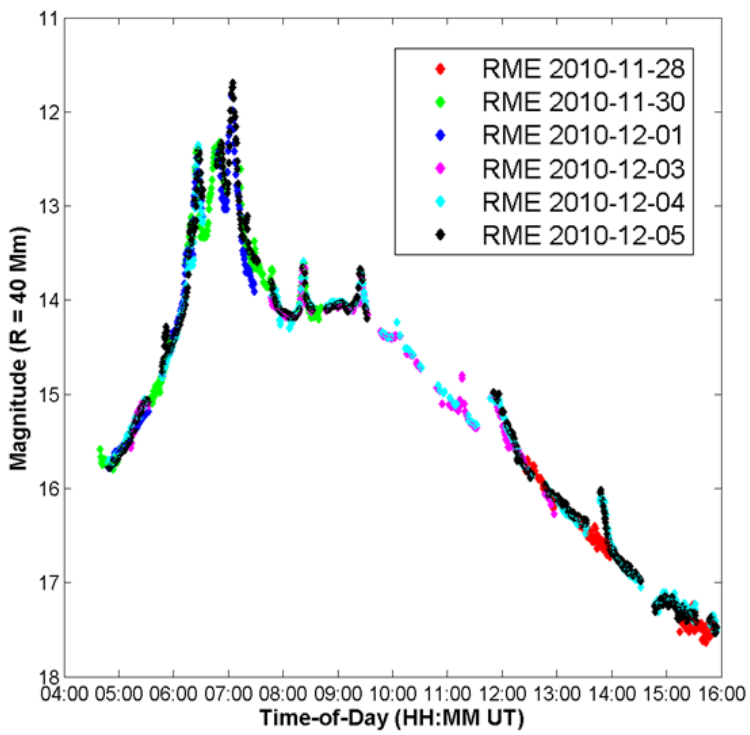

Figure 5 Galaxy 12 measurements from the AMOS RME site, acquired after the satellite had been re-located.

3.4 Galaxy 15 Photometric Measurements Confirming its Stabilized Status During its Free-Drift Phase

During the period the Galaxy 15 satellite was drifting and threatening other GEO satellites, multiple optical signatures were acquired as part of a focused study using a 0.28 m Raven-class telescope [9] located on Kirtland AFB near Albuquerque NM. Figure 6 shows the data measured on four consecutive nights (2011 Oct 29 – Nov 01). Note that the signatures from all four of these nights show a very consistent, repeatable shape. As discussed in the previous section, this implies that the satellite was maintaining a stable attitude during this time period. Other observations obtained from New Mexico and Maui also confirm that this was the case through most of this free-drift phase.

Therefore, even if the Intelsat owner-operator team did not know that this satellite remained stabilized during this period, these kinds of brightness observations could have been used to confirm that fact.

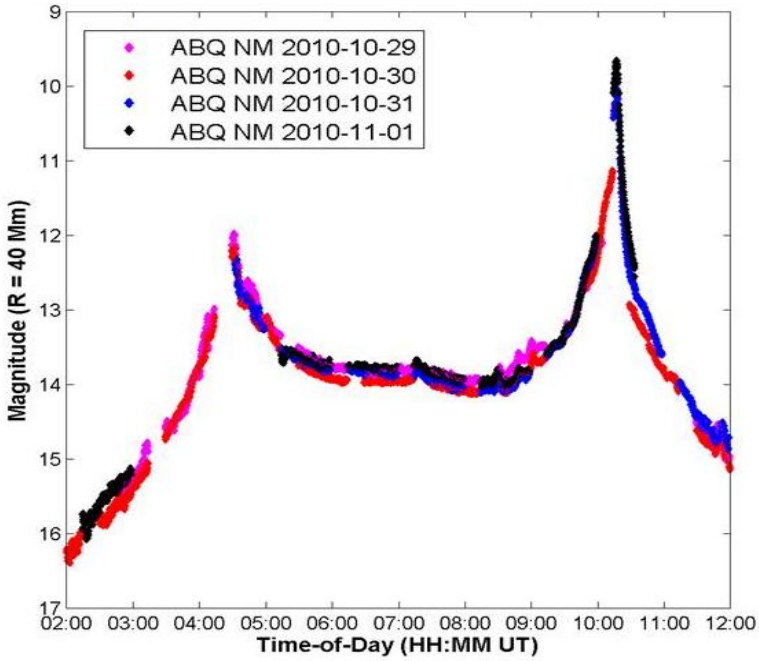

Figure 6 Galaxy 15 brightness measurements from Albuquerque NM.

3.5 Galaxy 15 Photometric Measurements Revealing the Loss of Attitude Stability and Nature of Rotational Motion

As mentioned previously, Galaxy 15's owners and operators predicted that, in the absence of proper ground-commanded maintenance activities, the satellite would eventually lose this ability to remain stabilized and keep its solar arrays properly facing the Sun. However, they could only predict when this "off-pointing" event would occur to an accuracy of roughly one month. Ultimately, the satellite finally lost stability on 2010 Dec 17, more than eight months after the initial anomaly. Fortunately, the weather on Maui permitted optical measurements to be collected from the AMOS 1.6 m telescope during the actual time when the off-pointing event occurred, as well as on the previous day. Figures 7 and 8 show these two signatures. The top plot in each shows the range-normalized visual magnitude plotted as a function of time, taken on 2010 Dec 16 — one day before the off-pointing event took place. The data in these top plots serve nicely as pre-event, baseline signatures. The bottom plots in Figures 7 and 8 show data from 2010 Dec 17, the day that the loss-of-stability event took place. The exact time of the off-pointing event on that day was 08:27 UTC [7], the time marked by a vertical dashed line in the plots.

As can be seen in the bottom panel of Figure 7, in the hours following the event, the temporal photometry shows a periodic-like variability in the brightness data that is clearly not present in the baseline data plotted above in the top panel. A more detailed analysis indicates that these post-event temporal variations are not consistent with a single constant frequency component, but rather can be explained only by summing multiple independent components with different and/or variable frequencies. This implies that *the satellite must have been in a multi-axis rotation state* (i.e., more complex than simple spin motion). This kind of rotation state is indeed consistent with a satellite that has just lost attitude control. In fact, Intelsat engineers believe the satellite was in a nutating state during after loss of stability [7], and this rotational motion persisted until Dec 23, when the batteries discharged sufficiently to prompt a system reset and recovery of control. Interestingly, during this six day period when the batteries were discharging, Galaxy 15 was believed to have been nutating for only 12 hours per day, from roughly from 08:23 to 20:23 UT [7]. This is because the loss of stability was caused by reaction wheel saturation, which would have naturally afflicted the satellite for only half of its 24-hour orbital period. During the remaining 12 hours (from roughly 20:23 until 08:23 the following day), the reaction wheels would have not suffered from saturation and the satellite likely recovered its stabilized state allowing it to partially re-charge its depleted batteries. Unfortunately, we know of no optical observations to confirm that this 12-hour oscillation actually occurred. However, it does explain the extended, six day period required for the satellite's batteries to discharge to a sufficient level for a system reset.

Figure 8 shows an expanded view of the data, focusing on a short period within about 30 minutes of the off-pointing event. Notably the bottom panel of Figure 8 shows two glints that occurred about 15 minutes after the loss of stability. These two specific glints do not appear in the previous day's baseline data plotted above, or in any other previous observations for that matter. Notably, these two glints are the very first optical manifestations of the onset of instability. The presence and detection of these glints illustrate that temporal photometry can conceivably indicate anomalous satellite behavior within remarkably short time periods, in this case 15 minutes, but only if baseline reference data are available for comparison.

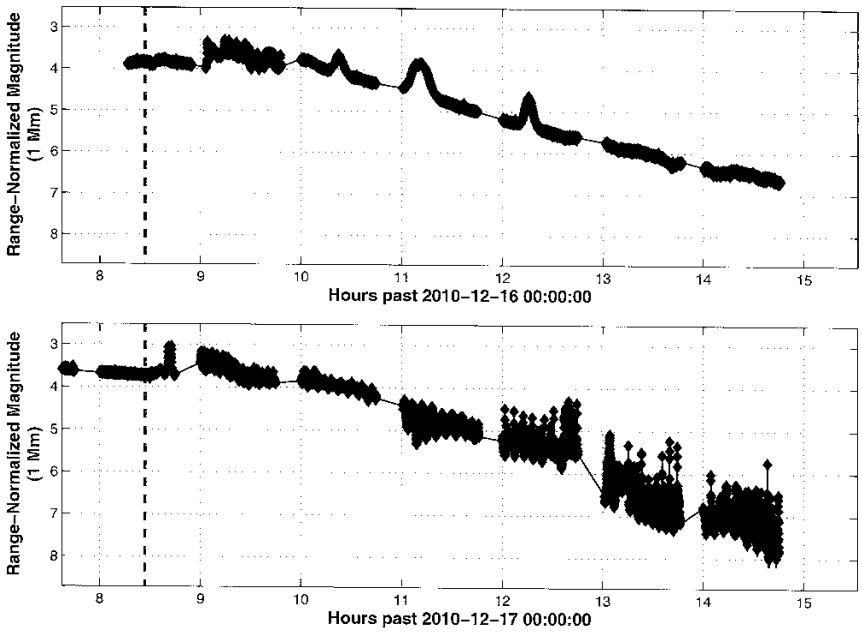

Figure 7 Galaxy 15 brightness signatures from Maui prior to, and during, the loss-of-stability off-pointing event.

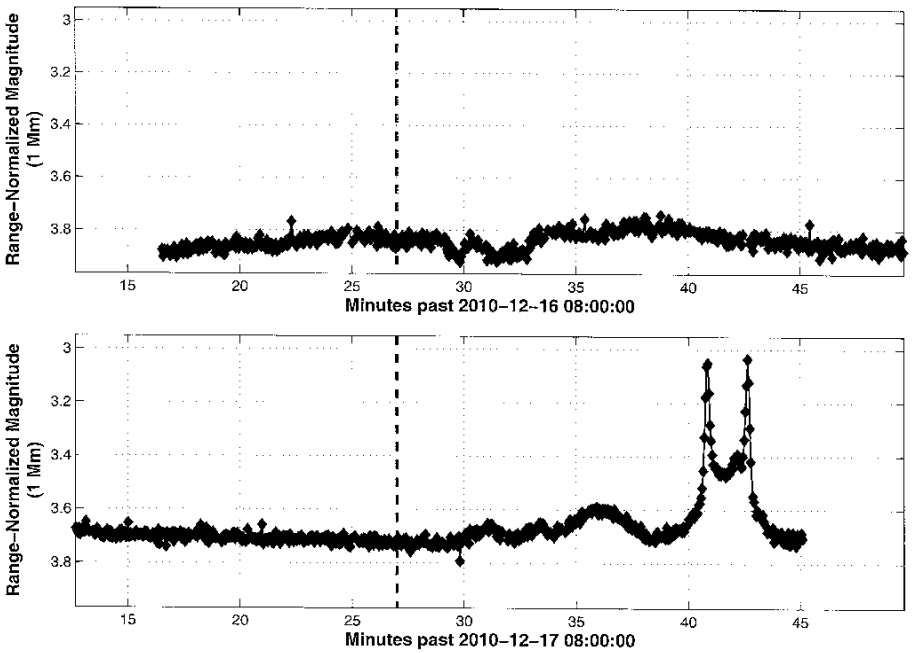

Figure 8 Expanded view of brightness signatures prior to, and during the off-pointing loss-of-stability event.

4 CONCLUSIONS

Optical observations of the Galaxy 15 satellite acquired before and during its recent anomaly and extended drift through the GEO belt demonstrate how temporal photometry can be used to evaluate the status of GEO satellites. Fortunately, acquiring such data does not require sophisticated or expensive instrumentation, and even small, Raven-class telescopes suffice for typical GEO satellites. Stabilized GEO satellites often show consistent, largely repeatable night-to-night brightness signatures when measured from a single ground-based site. However, these signatures can change shape over multi-day periods, in response to seasonal solar illumination variations. This means that significant changes in attitude (e.g., the onset of instability) for a GEO satellite can be detected by searching for significant changes in such night-to-night signatures. These include changes in the overall shape of the signature, the appearance/disappearance of glints, or the onset of periodic variations, as was seen for Galaxy 15 on the night that its reaction wheels finally saturated). In this regard, this analysis shows that it is often invaluable to have historical, baseline data, in order to fully evaluate signature changes and help determine the nature and cause of the satellite's new or anomalous behavior. In some cases, these baseline data sets can be measurements of the actual satellite of interest. However, sometimes baseline measurements are unavailable or incomplete, as in the case of Galaxy 15 where data sets just after launch only provided limited, sporadic coverage. In such cases, an identical or very similar satellite can be used to obtain proxy baseline measurements, as Galaxy 12 was employed in this analysis.

5 REFERENCES

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