NASA/TM—2014-218406

Investigation of Spiral Bevel Gear Condition Indicator Validation Via AC–29–2C Using Fielded Rotorcraft HUMS Data

Paula J. Dempsey
Glenn Research Center, Cleveland, Ohio

Daniel R. Wade
U.S. Army Aviation Engineering Directorate, Redstone Arsenal, Alabama

Lance J. Antolick and Josiah Thomas
RMCI, Inc., Huntsville, Alabama

November 2014

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include creating custom thesauri, building customized databases, organizing and publishing research results.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at *http://www.sti.nasa.gov*

- E-mail your question to *help@sti.nasa.gov*

- Fax your question to the NASA STI Information Desk at 443–757–5803

- Phone the NASA STI Information Desk at 443–757–5802

- Write to:
  STI Information Desk
  NASA Center for AeroSpace Information
  7115 Standard Drive
  Hanover, MD 21076–1320

NASA/TM—2014-218406

Investigation of Spiral Bevel Gear Condition Indicator Validation Via AC–29–2C Using Fielded Rotorcraft HUMS Data

Paula J. Dempsey
Glenn Research Center, Cleveland, Ohio

Daniel R. Wade
U.S. Army Aviation Engineering Directorate, Redstone Arsenal, Alabama

Lance J. Antolick and Josiah Thomas
RMCI, Inc., Huntsville, Alabama

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

November 2014

This work was sponsored by the Fundamental Aeronautics Program at the NASA Glenn Research Center.

Level of Review: This material has been technically reviewed by technical management.

Available from

NASA Center for Aerospace Information
7115 Standard Drive
Hanover, MD 21076–1320

National Technical Information Service
5301 Shawnee Road
Alexandria, VA 22312

Available electronically at http://www.sti.nasa.gov

Investigation of Spiral Bevel Gear Condition Indicator Validation Via AC–29–2C Using Fielded Rotorcraft HUMS Data

Paula J. Dempsey
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Daniel R. Wade
U.S. Army Aviation Engineering Directorate
Redstone Arsenal, Alabama 35898

Lance J. Antolick and Josiah Thomas
RMCI, Inc.
Huntsville, Alabama 35806

Executive Summary

This report documents work performed under a NASA Space Act Agreement (SAA) with the Federal Aviation Administration (FAA). The purpose of this work was to support validation and demonstration of rotorcraft Health and Usage Monitoring Systems (HUMS) for maintenance credits via "FAA Advisory Circular (AC) 29–2C, Section MG–15, Airworthiness Approval of Rotorcraft (HUMS)" (Ref. 1). The overarching goal of this work was to determine a method to validate condition indicators in the lab that better represent their response to faults in the field.

This report presents the analysis of gear condition indicator data collected on a helicopter when damage occurred in spiral bevel gears. The purpose of the data analysis was to use existing in-service helicopter HUMS flight data from faulted spiral bevel gears as a "Case Study," to better understand the differences between HUMS data response in a helicopter and a component test rig, the NASA Glenn Spiral Bevel Gear Fatigue Rig. The reason spiral bevel gear sets were chosen to demonstrate differences in response between both systems was the availability of the helicopter data and the availability of a test rig that was capable of testing spiral bevel gear sets to failure.

Based on this availability, a plan was put in place to design, fabricate and test comparable gear sets with comparable failure modes within the constraints of the test rig. The research objectives of the rig tests were to evaluate the capability of detecting gear surface pitting fatigue and other generated failure modes on spiral bevel gear teeth using gear condition indicators currently used in fielded HUMS. Results of this analysis were published in NASA Technical Memorandum NASA/TM—2014-218384 entitled, "Investigation of Spiral Bevel Gear Condition Indicator Validation via AC–29–2C Using Test Rig Damage Progression Test Data." The objective of the analysis presented in this paper was to reprocess helicopter HUMS data with the same analysis techniques applied to the spiral bevel rig test data. The damage modes experienced in the field were mapped to the failure modes created in the test rig.

A total of 40 helicopters were evaluated. Twenty helicopters, or tails, experienced damage to the spiral bevel gears in the nose gearbox. Vibration based gear condition indicators data was available before and after replacement. The other 20 tails had no known anomalies in the nose gearbox within the time frame of the datasets. These 20 tails were considered the baseline dataset.

Using tear down analysis (TDA) reports provided by the U.S. Army, the failure modes observed on the gear teeth and other components were summarized into a table and identified based on component

(gear or pinion) and type of damage. Some of the TDA reports were subjective with limited photographs. In some cases, other components, such as bearings and splines, were also noted as damaged.

The HUMS gear condition indicators evaluated included gear condition indicators (CI) Figure of Merit 4 (FM4), Root Mean Square (RMS) or Diagnostic Algorithm 1 (DA1) and ± 3 Sideband Index (SI3). Three additional condition indicators, not currently calculated onboard, were calculated from the archived data. These three indicators were ± 1 Sideband Index (SI1), the DA1 of the difference signal (DiffDA1) and the peak-to-peak of the difference signal (DP2P).

These six condition indicators were plotted per acquisition and date while the helicopter was in the flat pitch ground (FPG101) regime. If the data was available, these six gear condition indicators were also plotted per date while the helicopter was in the 120 knots true airspeed (120KTA) regime. The CI data from the 20 tails without damage was not individually plotted. Instead, histograms of the CI data from all 20 tails and a matrix comparing all six CIs were plotted for the pinion and the gear at the two regimes. Statistical tables of means and standard deviations were calculated before and after replacement for the helicopter with the damaged gears. A correlation matrix was also generated for the entire dataset showing the linear relationship between the CIs to damage state for the two regimes

Results found the CI DP2P, not currently available in the onboard HUMS, performed the best, responding to varying levels of damage on thirteen of the fourteen helicopters evaluated. Two additional CIs also not in the onboard system, DiffDA1and SI1, also performed well responding to 12 and 10 of the 14 helicopters evaluated, respectively. Of the three CIs currently available in the MSPU, DA1, FM4 and SI3, SI3, responded to eight, DA1 responded to six and FM4 responded to four of the 14 helicopters evaluated. FM4, the poorest performing CI, was not as responsive to damage as the other five CIs. Conversely, when compared to the other two, it was the only CI that responded to damage on two helicopters.

CI response could not be correlated to specific failure modes due to limited pictures and subjective descriptions found within the TDA. Flight regime did affect CI response to some gear faults. Due to the range of operating conditions for each regime, more studies are required to determine their sensitivity to regimes.

This is the second of three final reports published on the results of this project. In the third report, results from the rig and helicopter data analysis will be compared for differences and similarities in CI response. Observations, findings and lessons learned using subscale rig failure progression tests to validate helicopter gear condition indicators will be presented.

Contents

Acronyms

120KTA	120 knots true airspeed regime
AC	Advisory Circular
AGMA	American Gear Manufacturers Association
CAA	Civil Aviation Authority
CBM	Condition-Based Maintenance
CI	Condition Indicator
DA1	CI Diagnostic Algorithm 1 calculated from the root-mean-square
DiffDA1	CI DA1 of the difference signal
DiffP2PC	CI Peak-to-peak of difference signal
DP2P	CI Peak-to-peak of difference signal
FAA	Federal Aviation Administration
FM4	CI Figure of Merit 4
FPG100	Flat pitch ground 100 percent rotor speed regime
FPG101	Flat pitch ground 101 percent rotor speed regime
GL	Gear Left
GR	Gear Right
HUMS	Heath and Usage Monitoring System
MDSS	Mechanical Diagnostic System Software
MSPU	Modern Signal Processing Unit
NASA	National Aeronautics and Space Administration
NGB	Nose Gearbox
PL	Pinion Left
PR	Pinion Right
RMS	CI Root-Mean Square
SAA	Space Act Agreement
SI	CI Sideband Index calculated from averaged ± 3 sidebands around mesh
SI1	CI Sideband Index calculated from averaged ± 1 sidebands around mesh
SI1st	CI Sideband Index calculated from averaged ± 1 sidebands around mesh
SI3	CI Sideband Index calculated from averaged ± 3 sidebands around mesh
SI3rd	CI Sideband Index calculated from averaged ± 3 sidebands around mesh
TDA	Tear Down Analysis
TSA	Time Synchronous Averaged Data
U.S.	United States

1.0 Background

This report documents the results of an analysis on gear condition indicator data collected on a helicopter when damage occurred to spiral bevel gear sets. This analysis was performed as a collaborative effort with the Federal Aviation Administration (FAA) and the U.S. Army under a NASA Space Act Agreement with the FAA. This work was performed to support validation and demonstration of rotorcraft Health and Usage Monitoring Systems (HUMS) for maintenance credits via “FAA Advisory Circular (AC) 29–2C, Section MG–15, Airworthiness Approval of Rotorcraft (HUMS)” (Ref. 1). Maintenance

credits are modified inspection and removal criteria of components based on HUMS measured condition and actual usage. Maintenance credit validation includes providing evidence of damage detection algorithm effectiveness using acceptance limits, trending techniques, tests and demonstration methods. For dynamic transmission components, these methods can include using data from naturally occurring aircraft faults and component fault testing on a test stand (Ref. 2). Due to time, cost and safety concerns, evidence via actual service on aircraft is typically replaced with rig tests, where a measurable and known component fault is checked against the algorithm and its thresholds.

The Civil Aviation Authority (CAA) also published a document to provide guidance using vibration health monitoring (VHM), defined as "data generated by processing vibration signals to detect incipient failures or degradation of mechanical integrity," for maintaining helicopter rotor and drive systems (Ref. 3). These vibration signatures are referred to as "condition indicators" (CI) that develop when a fault occurs on a component and interacts with its operational environment. Within this CAA document, fault testing is also mentioned as a validation method to demonstrate algorithm damage detection effectiveness for specific faults.

The overarching goal of this work was to define condition indicator validation methods in the test rig that better represent their response to faults in the field. Due to differences in both systems and their operational environments, response of a CI to a fault in a test rig may not be representative of a CI response in a helicopter. For these situations, CI performance limitations must be defined to understand the risks in using a test rig validated CI on a helicopter. One obstacle in determining if CI response to a fault in a test rig is comparable to its response when measured on a helicopter is the limited availability of CI data from a faulted component flying on a helicopter.

Previous analyses were performed on rotorcraft spiral bevel gear condition indicator performance in support of the U.S. Army's Condition-Based Maintenance (CBM) program (Refs. 4 and 5). CI performance was evaluated using fielded helicopter datasets recorded when damage occurred on spiral bevel gear (pinion/gear) teeth located in several helicopter nose gearboxes. The nose gearboxes are mounted in the front of each engine to reduce the power turbine speed and change the drive angle. In addition to thousands of hours of CI data collected before and after spiral bevel gear replacement, tear down analyses were performed, documenting the extent of damage to the gear and pinion teeth. Within the timeframe when the faulted components were occurring in the helicopters, NASA Glenn Research Center had an existing and available component test rig for testing spiral bevel gears, the Spiral Bevel Gear Fatigue Test Rig.

Using this existing in-service HUMS flight data from faulted spiral bevel gears, a plan was put in place to design and test comparable gear sets within the constraints of the test rig. The drivers for testing in the component test rig, as opposed to a full-scale system, were based on the cost and time it would take to design, develop and build testing capabilities combined with the time required to initiate and progress a defect in the actual helicopter component. The availability of fielded helicopter HUMS CI data when spiral bevel gear damage occurred, the availability of the NASA Glenn Spiral Bevel Gear Fatigue Rig and the availability of the same HUMS installed on the helicopters for use in the rig made this a cost effective proposition within a reasonable timeframe. The requirements for spiral bevel gear damage progression tests to be performed in the NASA Glenn Spiral Bevel Gear Fatigue Test Rig are outlined in Reference 6. Results of these tests can be found in Reference 7.

In the analysis presented in this report, fielded helicopter HUMS data from 40 helicopters are processed with the same techniques applied to spiral bevel rig test data (Ref. 7). Twenty helicopters experienced damage to the spiral bevel gears, while the other 20 tails had no known anomalies within the time frame of the datasets.

2.0 Objectives and Approach

The objective of the analysis presented in this paper was to re-process helicopter health monitoring data with comparable analysis techniques applied to health monitoring data collected during spiral bevel gear damage progression tests performed in the NASA Glenn Spiral Bevel Gear Fatigue test Rig (Ref. 7). HUMS data was collected on 20 helicopters while damage occurred and after component replacement. Failure modes observed on the gear teeth and other gearbox components were documented in tear down analyses (TDA) provided by the U.S. Army. The specific objectives of the analysis are as follows:

a) Summarize gear tooth damage modes using tear down analysis reports.
b) Separate the data per tail into health states: damaged (before replacement); undamaged (after replacement).
c) Evaluate the capability of detecting gear surface pitting fatigue and other generated failure modes on spiral bevel gear teeth using gear condition indicators (CI): Figure of Merit 4 (FM4), Root Mean Square (RMS) or Diagnostic Algorithm 1 (DA1), ± 1 Sideband Index (SI1) and ± 3 Sideband Index (SI3).
d) Evaluate the capability of detecting gear surface pitting fatigue and other generated failure modes on spiral bevel gear teeth using two new gear condition indicators not currently collected onboard: DA1 of the difference signal (DiffDA1) and the peak-to-peak of the difference signal (DP2P).
e) Evaluate the effect of regimes on CI performance.
f) Cluster comparable damage modes from different gear tests.

3.0 Gearbox Description

The component under investigation is the spiral bevel gear set in the nose gearbox of the Apache helicopter (AH64). A photograph of the location of the nose gearbox in the helicopter is shown in Figure 1 (Ref. 6). The failure mode was verified by the tear down analysis (TDA) documentation of the gear and pinion teeth damage. Key operational parameters such as torque, speed, oil temperatures and pressures, on the helicopters were provided. For the aircraft used in this investigation, the HUMS data was acquired, stored, tracked, trended and monitored separately from the operational data (Ref. 8).

In addition to HUMS data, measurements were made to characterize helicopter static structural dynamics. Transfer-path measurements were made on one AH64D left and right nose gearboxes through excitation from a piezoelectric shaker and impact testing. The left and right gearboxes mirror each other. The measurements were made on the helicopter for another purpose, to help select ideal bearing defect-detection frequency bands (Ref. 9). Additional measurements were made on a nose gearbox installed in a fixture at NASA Glenn. External measurements made on the helicopter were compared to external measurements made on the fixture under the same conditions. The test fixture enabled the application of measured torques—common during an actual operation and the simulation of other environmental conditions experienced in the field that could not be made on the helicopter. Measurements were taken and compared while impacting the gear set near mesh to simulate gear meshing dynamics. Frequency Response functions were calculated for all measurements and compared using the Kolmogorov–Smirnov statistical test, a nonparametric test for comparing probability distributions (Ref. 10). The frequency response functions measured under comparable conditions of both systems were found to be consistent, while gear vibration transfer path dynamics were found to be load dependent within some frequency bands (Ref. 11).

Figure 1.—Location of spiral bevel gear set in helicopter

4.0 Instrumentation and Data Acquisition

All of the aircraft HUMS data was collected and processed with a helicopter HUMS, referred to as the Modern Signal Processing Unit (MSPU). The MSPU system is an onboard rotorcraft HUMS system that acquires, digitizes and processes the tachometer pulses and accelerometer data. The data is then downloaded to a ground station, referred to as PC-GBS, for further analysis. The ground station software provides the graphical user interface for the user to archive, process and analyze the onboard data.

Although the MSPU monitors all of the dynamic mechanical components of the drive train in the helicopter, the focus for this analysis is limited to the components in the nose gearbox of the helicopter. For the MSPU system, one accelerometer is installed on the housing of the right nose gearbox, and one is installed on the housing of the left nose gearbox. The accelerometers are mounted radially with respect to the gear. Accelerometer frequency range is 0.5 to 5 KHz with a resonant frequency of 26 KHz. One magnetic tachometer is installed to measure shaft speed. Gear ratios are used to process the data at the correct speed for each component. Time synchronous averaging (TSA) of the vibration data collected from the left and right accelerometer is performed in the MSPU system for the pinions and the gears using their shaft speeds. TSA methods will be further discussed in Section 7.0, “Analyses of Condition Indicators.”

5.0 Failure Modes

The failure modes to be investigated were defined by class (contact fatigue), general mode (macro pitting) and degree (progressive) per American Gear Manufacturers Association (AGMA) standards for gear wear terminology (Ref. 12). Table 1 illustrates the types of damage documented from TDA pictures. Scuffing is not a fatigue failure mode, where material is detached from the gear tooth contact, but rather the transferring of metal due to welding and tearing due to lubricant-film failure. It should be noted that

some of the TDA reports had limited photographs of the type of damage described within the report and used different terminology to describe the observed damage.

A 30 year survey of helicopter failure investigations found 55 percent of component failure was due to fatigue type failure modes described as pitting and spalling, while fretting or scuffing was found as the third highest factor (Ref. 13). The majority of these failures, over 34 percent, were found in the engine and transmission. Fatigue failures found on gear and pinion teeth were found to initiate due to alignment, manufacturing defects and lubrication issues (Ref. 13).

Definitions for tooth surface pitting modes (Ref. 12) are summarized as follows:

- Initial—Pits less than 1 mm in diameter.
- Progressive—Pits in different shapes/sizes greater than 1 mm in diameter.
- Flake—Pits that are shallow thin flakes.
- Spalling—Pits that cover tooth contact surfaces that exceed progressive pitting.

A table that connects condition indicator response to maintenance action was provided in reference (Ref. 8). It is shown here to provide a feel for the affect the damaged spiral bevel gears had on the helicopters discussed in this report. Per the definitions listed in Table 2, the damaged spiral bevel gear sets "Operational Capability," listed in column one, were limited to "Reduced Functionality." The helicopter component damage slowly progressed, where the damage was detectable within a certain size and the component performed its intended function with a level of detectable damage.

TABLE 1.—OBSERVED GEAR FAILURE MODES (REF. 12)

Class	Mode	Degree
Contact Fatigue	Subcase Fatigue	
	Micropitting	
	Macropitting	Initial Progressive Flaking Spalling
Scuffing	Scuffing	Mild Moderate Severe

TABLE 2.—DAMAGE LEVELS (REFS. 8 AND 14)

Operational capability	Maintenance action required	Time horizon for maintenance	Impact to components
Fully functional	No maintenance required	Remaining life	No perceptible impact to components/mating parts
Functional with degraded performance	Monitor frequently	> 100 hr	Eventual component/mating part degradation from light metal contamination /wear/vibration translation
Reduced functionality	Maintain as soon as practical	10 hr < X < 100 hr	Moderate metal contamination resulting in accelerated component/mating part degradation
Non-critical ***and*** non-mission aborting failure mode	Non-urgent maintenance	0 < X < 10 hr	Immediate component/mating part degradation
Critical ***or*** mission aborting failure mode	Maintain immediately	None	Heavy metal contamination resulting in catastrophic potential

6.0 Summary of Helicopter Gear Sets

Table 3 is a summary of the helicopters analyzed with damaged spiral bevel gear sets. The first column identifies the tail number. The second column identifies if the damaged gear set was found in the left or right nose gearbox. The next four columns indicate the four components investigated: right pinion (PR), right gear (GR), left pinion (PL), left gear (GL). An x in the column indicates damaged was observed on this component prior to replacement. A summary of the damage described in the TDA is listed in the last column of Table 3.

The tail number in the first column is color coded based on component and damage modes listed in Table 4. The tails greyed out indicate issues with these data sets. For tail number 3, the tail was replaced a second time after the initial replacement. Tail number 12 came from an AH64A model, while the other tails were AH64D models. For tails numbers 9, 11, 17 and 19, less than 7 data points were recorded prior to replacement.

TABLE 3.—SUMMARY OF HELICOPTERS WITH SPIRAL BEVEL GEAR DAMAGE

Tail no.	Component	PR	GR	PL	GL	Damage
1	Left			x	x	Gear and pinion teeth uneven wear and scuffing; output spline wear
2	Left			x	x	Gear and pinion severely damaged
3	Left			x	x	Gear and pinion teeth spalling; output spline wear, output duplex bearing IR spalling
4	Left			x		Gear wear and pinion pitting; output bearing IR spalling
5	Left			x		Pinion pitting; spline damage
6	Right	x				Moderate wear and scuffing on pinion
7	Right	x	x			Gear and pinion wear and pitting; gear scuffing
8	Right	x	x			Gear and pinion teeth scuffing; input bearing roller spalling
9	Right	x	x			Gear and pinion teeth uneven wear and scuffing; output duplex bearing ball damage
10	Right	x				Pinion moderate scuffing; output duplex bearing ball spalling
11	Right		x			Gear light scuffing; output duplex bearing IR and ball spalling
12	Right	x	x			Gear and pinion spalling
13	Right	x	x			Gear tooth chipped on toe side of gear, gear and pinion scuffing, pinion spalling
14	Left			x	x	Gear and pinion spalling
15	Left			x	x	Gear and pinion scuffing and spalling
16	Left			x	x	Gear and pinion severe scuffing on edge of teeth
17	Left			x		Pinion severe spalling
18	Left			x		Pinion severe spalling
19	Right	x	x			Pinion severe spalling/root wear (tip interf.); Gear pitting
20	Right	x	x			Pinion and gear severe pitting

TABLE 4.—COMPONENT AND DAMAGE MODE COLOR CODES

Color code	Damage modes
	Gear and pinion pitting, spalling or scuffing
	Pinion only pitting, spalling or scuffing

7.0 Analyses of Condition Indicators

Vibration data was collected at sample rates that provided sufficient vibration data for calculating time synchronous averages (TSA) by applying techniques for averaging vibration signals over several revolutions of the shaft to improve the signal-to-noise ratio (Ref. 15). Vibration signals synchronous with the shaft speed intensify relative to non-periodic signals. Using the magnetic tachometer, the vibration signal collected from the accelerometer is interpolated into a fixed number of points per shaft revolution. Since helicopter gears generate vibration signatures synchronous with gear rotational speed, all the gear CIs in the MSPU system use TSA data.

Signal processing techniques used to extract useful information to calculate a gear CI from the vibration signal are discussed in detail in Reference 16. Some gear CIs are calculated directly from the TSA signal, such as Root Mean Square (RMS). Some are calculated from the TSA converted to the frequency domain, such as Sideband Index (SI). Some convert the TSA signal to the frequency domain, filter specific frequencies, convert it back to the time domain, then calculate a statistical parameter from this data, such as FM4 (Refs. 15 to 17). These four CIs are calculated from the MSPU system and will be further discussed.

FM4 is one CI used to indicate gear tooth damage. Figure 2, on the left, shows a block diagram of the steps required to calculate FM4, a common vibration algorithm used in commercial HUMS (Ref. 15). FM4 is the kurtosis of the residual or difference signal normalized by the square of the variance. Kurtosis is the fourth statistical moment of a signal about its mean (Ref. 16). The purpose of taking the kurtosis of any signal is to identify the presence of peaks. When normalized by the squared variance, the kurtosis becomes a measure of both the number and amplitude of the peaks, where peaks indicate a gear anomaly (Ref. 18). FM4 has shown good results in full scale test stands when single tooth faults are introduced, but poorly on fleet data (Ref. 19 and 5). This is most likely due to the level of damage to the gear teeth. FM4 responds well to localized faults, but is a poor indicator for faults distributed across multiple teeth (Ref. 7).

RMS, referred to as DA1 in the MSPU system, is another CI used to indicate gear tooth damage. Figure 2, on the right, shows a block diagram of the steps required to calculate RMS.

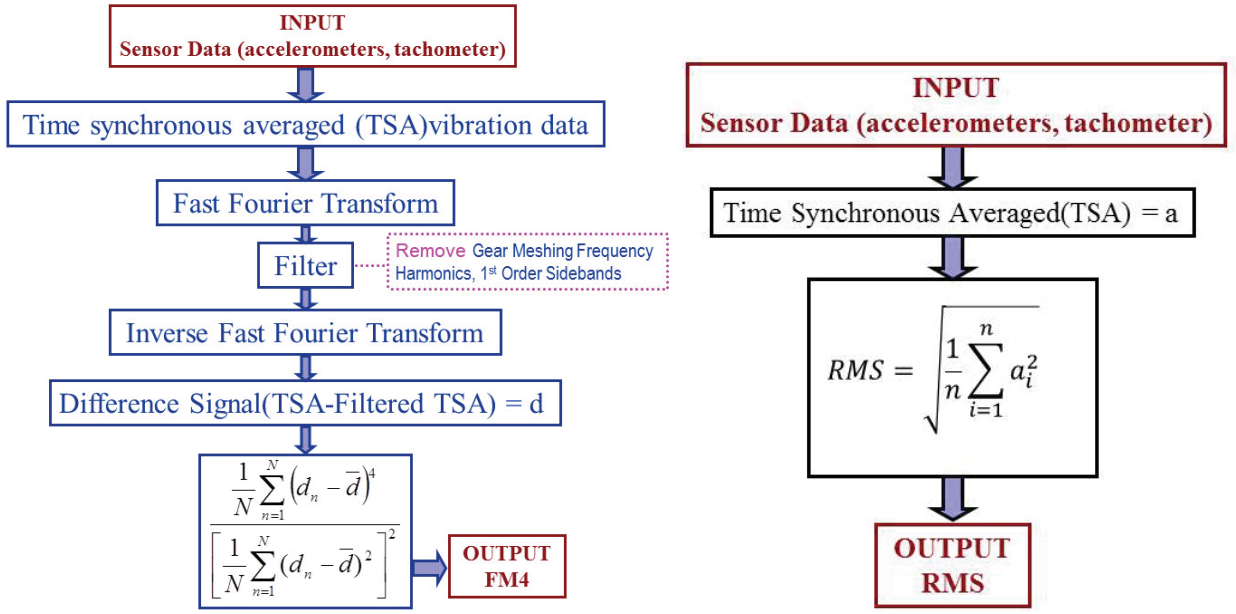

Figure 2.—FM4 and RMS Calculation

Sideband index (SI) is another CI used to indicate gear tooth damage (Ref. 5). SI is a frequency domain based CI. The CI value is an average value of sideband amplitudes about the fundamental gear mesh frequency. All gears generate a dominant gear mesh (GM) frequency in the vibration signature due to each tooth engaging the gear it is driving as the pinion and gear mesh. The gear (or pinion) mesh frequency is equal to the number of teeth multiplied by its speed. The number of sidebands included in the calculation of the sideband CI can vary with different health monitoring systems. The MSPU system only calculates averages of ± 3 sidebands, referred to as SI or ± 3 Sideband Index or SI3.

Three additional condition indicators, not currently calculated onboard, were calculated from the archived data. One of the three is ± 1 sideband or SI1. Figure 3 shows a block diagram of the steps required to calculate SI1. The other two were the DA1 of the difference signal (DiffDA1) and the peak-to-peak of the difference signal (DP2P). Both use the same process listed for FM4 in the block diagram shown in Figure 2, except for the last step. The last step is replaced with the RMS of the difference signal (d) for DiffDA1 and the maximum difference signal (d) value minus the minimum (d) value for the DP2P.

CI data was also calculated for two regimes before and after replacement: 101 percent rotor speed flat pitch ground (FPG101) and 120 knots true airspeed (120KTA). Parameters for these two flight regimes are shown in Table 5.

Condition Indicators FM4, RMS, SI1, SI3, DiffDA1 and DP2P for the left gear (GL), left pinion (PL), right gear (GR) and right pinion (PR) were plotted for all 20 helicopters per acquisition and date, while the helicopter was in the flat pitch ground (FPG101) regime. The same CIs were also plotted per date while the helicopter was in the 120KTA regime if this data was available. These plots are located in Appendix A, “Plots of MSPU Condition Indicators from Damaged Tail.”

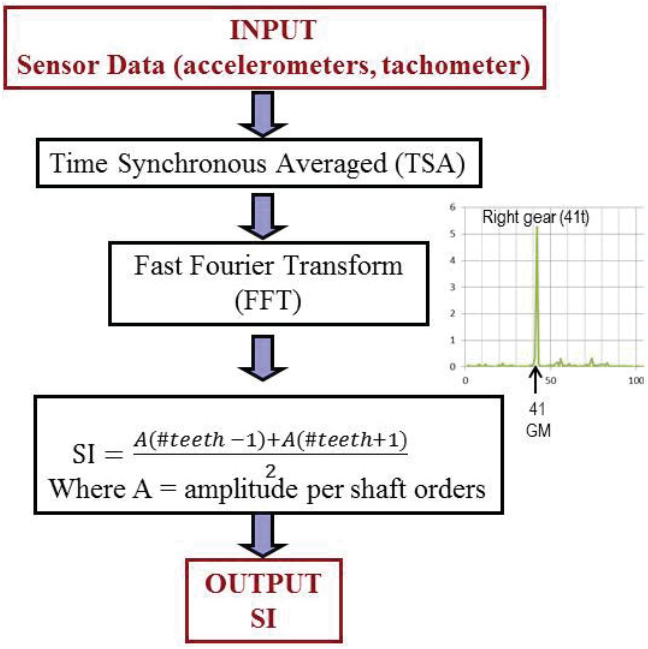

Figure 3.—SI1 calculation.

TABLE 5.—HUMS REGIMES

Parameter	Regimes	
	FPG101	120KTA
Radar Alt, ft	0 to 5	6 to 30,000
Torque, %	5 to 50	50 to 75
Average Torque, %	15	68
True Airspeed, kn	–30 to 30	111 to 129
Main Rotor Speed, %	98 to 102	98 to 102
Vertical Speed, ft/sec	–5 to 5	–5 to 5

Statistical tables of CI mean and standard deviation values were calculated before and after replacement for condition indicators FM4, RMS, SI1, SI3, DiffDA1 and DP2P for the GL, GR, PL and PR. These tables are limited to the tails that are not greyed out in Table 3. These tables are located in Appendix B, “CI Statistical Parameters Before and After Replacement.” A representative example of the data contained in the Appendix A and Appendix B will be reviewed for helicopter number 18. The left pinion only was spalled prior to replacement on tail number 18.

Condition Indicators FM4, RMS, SI1, SI3 for the GL, PL, GR, and PR measured on helicopter number 18 are plotted in Figure 4 to Figure 9. These plots correspond to Figure A.18.1 to Figure A.18.6 found in Appendix A. Note that the square on the x-axis indicates the last acquisition prior to inspection and replacement of the gearbox.

Mean and standard deviation values for Condition Indicators FM4, RMS, SI1, SI3, DiffDA1 and D2P2 for the GL, PL, GR and PR are listed in Table 6 to Table 11. These tables correspond to Table B.13 found in Appendix B. If the CI responded to the damaged component, in this case the left pinion, it is highlighted in red before gearbox replacement and blue after gearbox replacement. The table columns identify the component location, CI name, before or after replacement start acquisition and end acquisition, the number of points before and after replacement, the mean value for the component CI and the standard deviation for the component CI. For example, the PL FM4 mean value was 4.01 before replacement with a 0.32 standard deviation.

Per Table 3, severe spalling was observed on the left pinion teeth prior to gearbox replacement. FM4, SI3, DiffDA1 and DP2P CI values for the left pinion all responded prior to replacement. All four exceeded threshold limits set per historical fleet data. FM4 exceeded 4.5, SI1 and SI3 exceeded 6, DiffDA1 exceeded 15 and DP2P exceeded 100 prior to replacement for the FPG regime. No120KTA regime data was available prior to replacement.

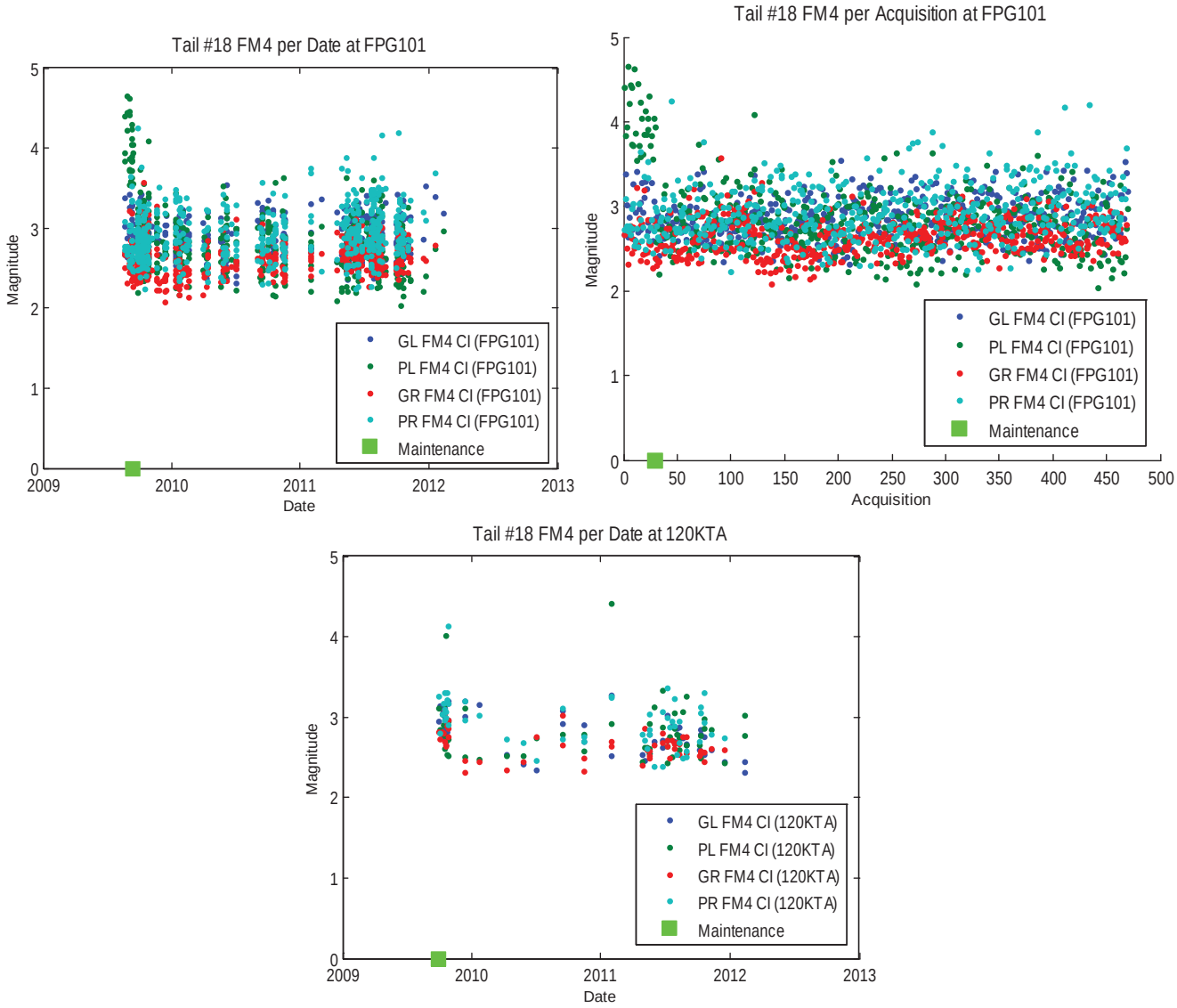

Figure 4.—Tail Number 18 Plots of FM4 per Date, Acquisition and Regime

TABLE 6.—FM4 MEAN AND STANDARD DEVIATION FOR TAIL NUMBER 18

Location	CI name	Status	Index start	Index end	No. points	Mean	STD
PR	FM4	Before	1	29	29	2.84	0.31
PR	FM4	After	30	487	457	2.93	0.32
GR	FM4	Before	1	29	29	2.63	0.23
GR	FM4	After	30	485	455	2.63	0.20
PL	FM4	Before	1	29	29	4.01	0.32
PL	FM4	After	30	485	455	2.77	0.31
GL	FM4	Before	1	29	29	2.94	0.26
GL	FM4	After	30	485	455	2.86	0.24

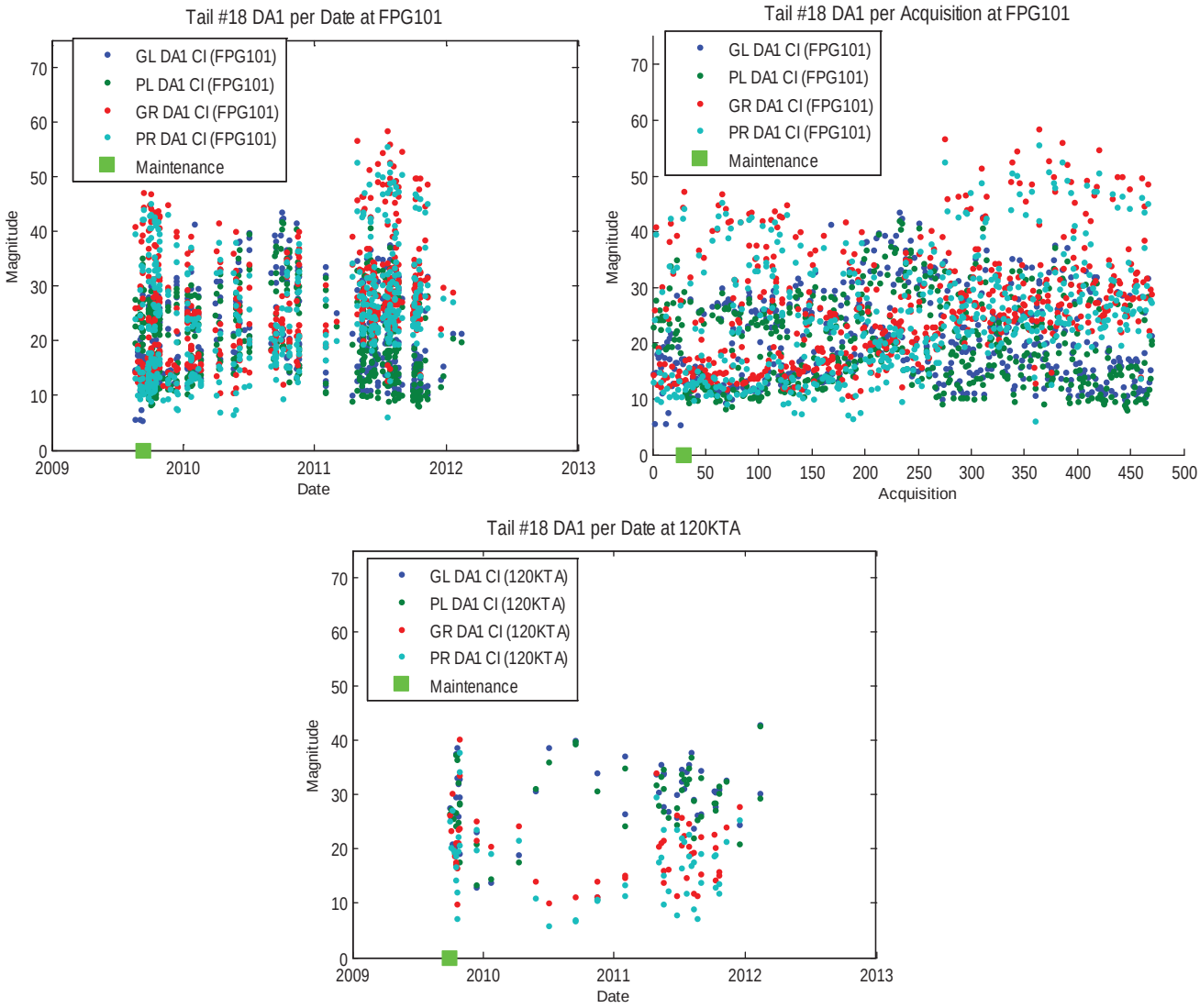

Figure 5.—Tail Number 18 Plots of DA1 per Date, Acquisition and Regime

TABLE 7.—DA1 MEAN AND STANDARD DEVIATION FOR TAIL NUMBER 18

Location	CI name	Status	Index start	Index end	No. points	Mean	STD
PR	DA1	Before	1	29	29	20.86	11.61
PR	DA1	After	30	488	458	25.09	10.14
GR	DA1	Before	1	29	29	22.81	11.57
GR	DA1	After	30	488	458	27.25	10.01
PL	DA1	Before	1	29	29	24.43	4.17
PL	DA1	After	30	488	458	19.67	7.78
GL	DA1	Before	1	29	29	15.71	5.14
GL	DA1	After	30	490	460	21.20	7.97

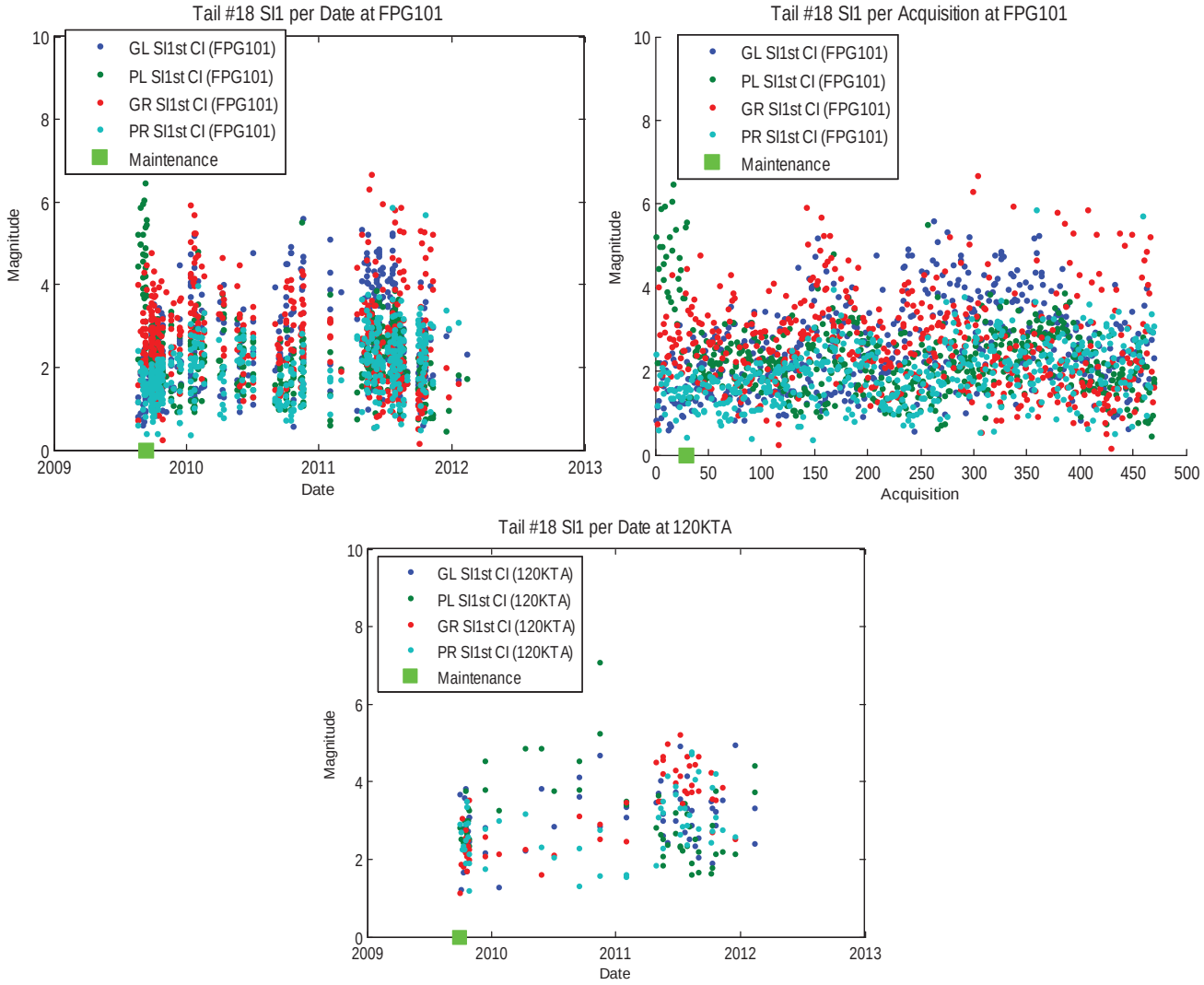

Figure 6.—Tail Number 18 Plots of SI1 per Date, Acquisition and Regime

TABLE 8.—SI1 MEAN AND STANDARD DEVIATION FOR TAIL NUMBER 18

Location	CI name	Status	Index start	Index end	No. points	Mean	STD
PR	SI1	Before	1	29	29	1.51	0.44
PR	SI1	After	30	488	458	1.97	0.72
GR	SI1	Before	1	29	29	2.65	0.82
GR	SI1	After	30	488	458	2.67	1.10
PL	SI1	Before	1	29	29	4.54	1.04
PL	SI1	After	30	488	458	2.17	0.69
GL	SI1	Before	1	29	29	1.51	0.62
GL	SI1	After	30	490	460	2.66	1.03

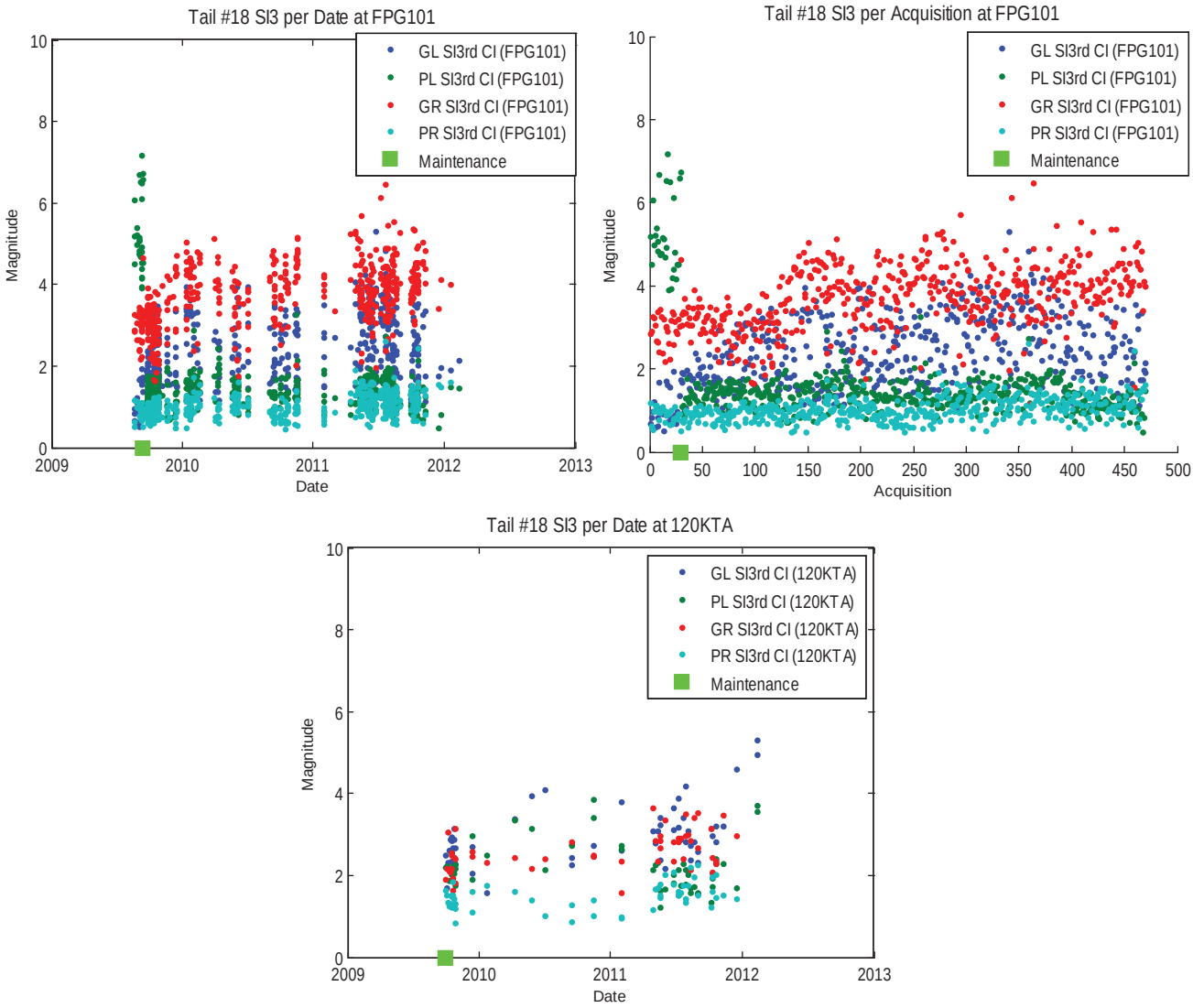

Figure 7.—Tail Number 18 Plots of SI3 per Date, Acquisition and Regime

TABLE 9.—SI3 MEAN AND STANDARD DEVIATION FOR TAIL NUMBER 18

Location	CI name	Status	Index start	Index end	No. points	Mean	STD
PR	SI3	Before	1	29	29	0.89	0.18
PR	SI3	After	30	488	458	1.04	0.28
GR	SI3	Before	1	29	29	2.99	0.47
GR	SI3	After	30	488	458	3.74	0.77
PL	SI3	Before	1	29	29	5.23	0.92
PL	SI3	After	30	488	458	1.38	0.32
GL	SI3	Before	1	29	29	1.04	0.39
GL	SI3	After	30	490	460	2.43	0.82

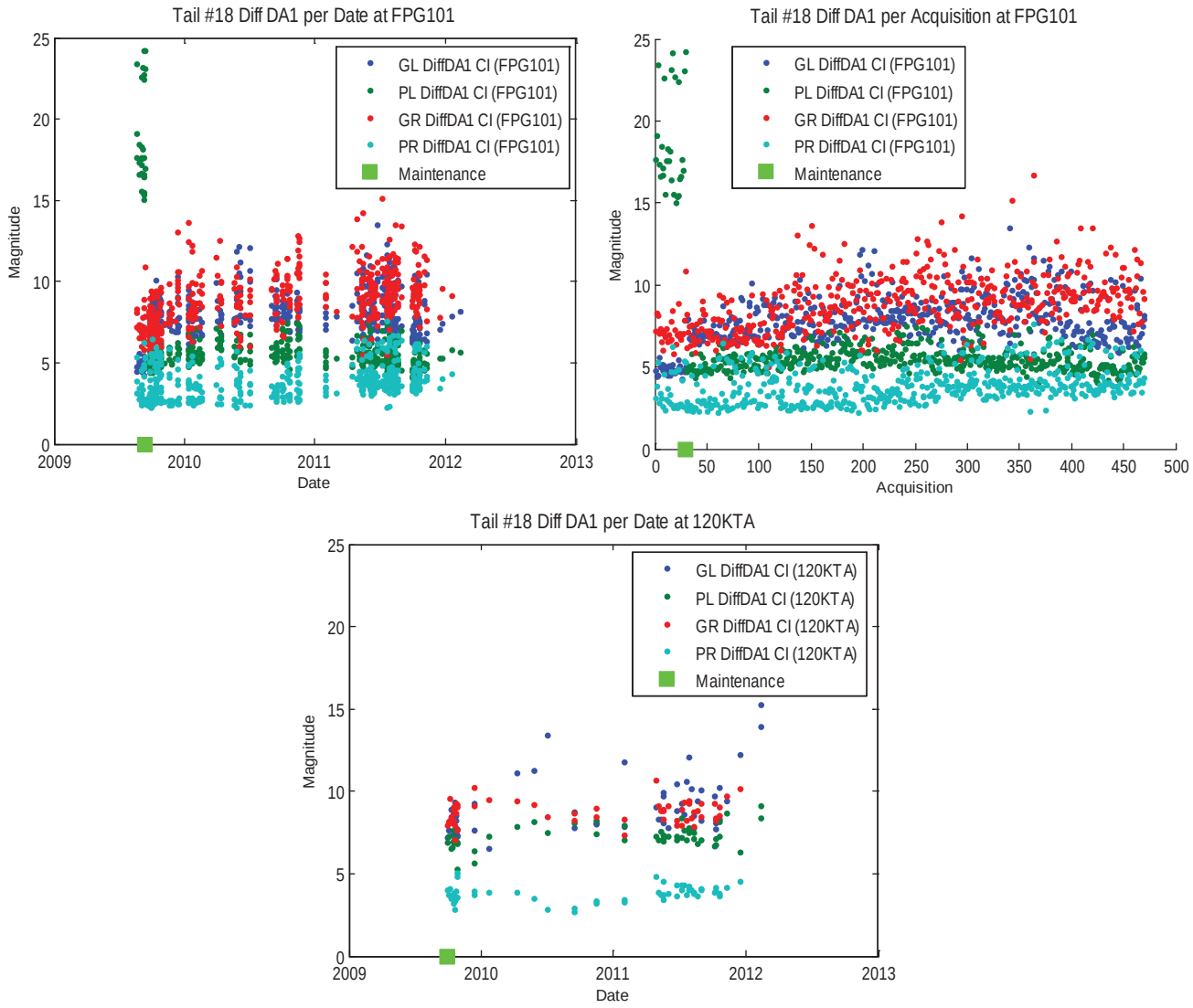

Figure 8.—Tail Number 18 Plots of DiffDA1 per Date, Acquisition and Regime

TABLE 10.—DiffDA1 MEAN AND STANDARD DEVIATION FOR TAIL NUMBER 18

Location	CI name	Status	Index start	Index end	No. points	Mean	STD
PR	DiffDA1	Before	1	29	29	3.56	1.11
PR	DiffDA1	After	30	488	458	3.87	1.03
GR	DiffDA1	Before	1	29	29	7.27	0.98
GR	DiffDA1	After	30	488	458	8.93	1.67
PL	DiffDA1	Before	1	29	29	18.68	3.04
PL	DiffDA1	After	30	488	458	5.47	0.63
GL	DiffDA1	Before	1	29	29	4.88	0.30
GL	DiffDA1	After	30	490	460	8.06	1.25

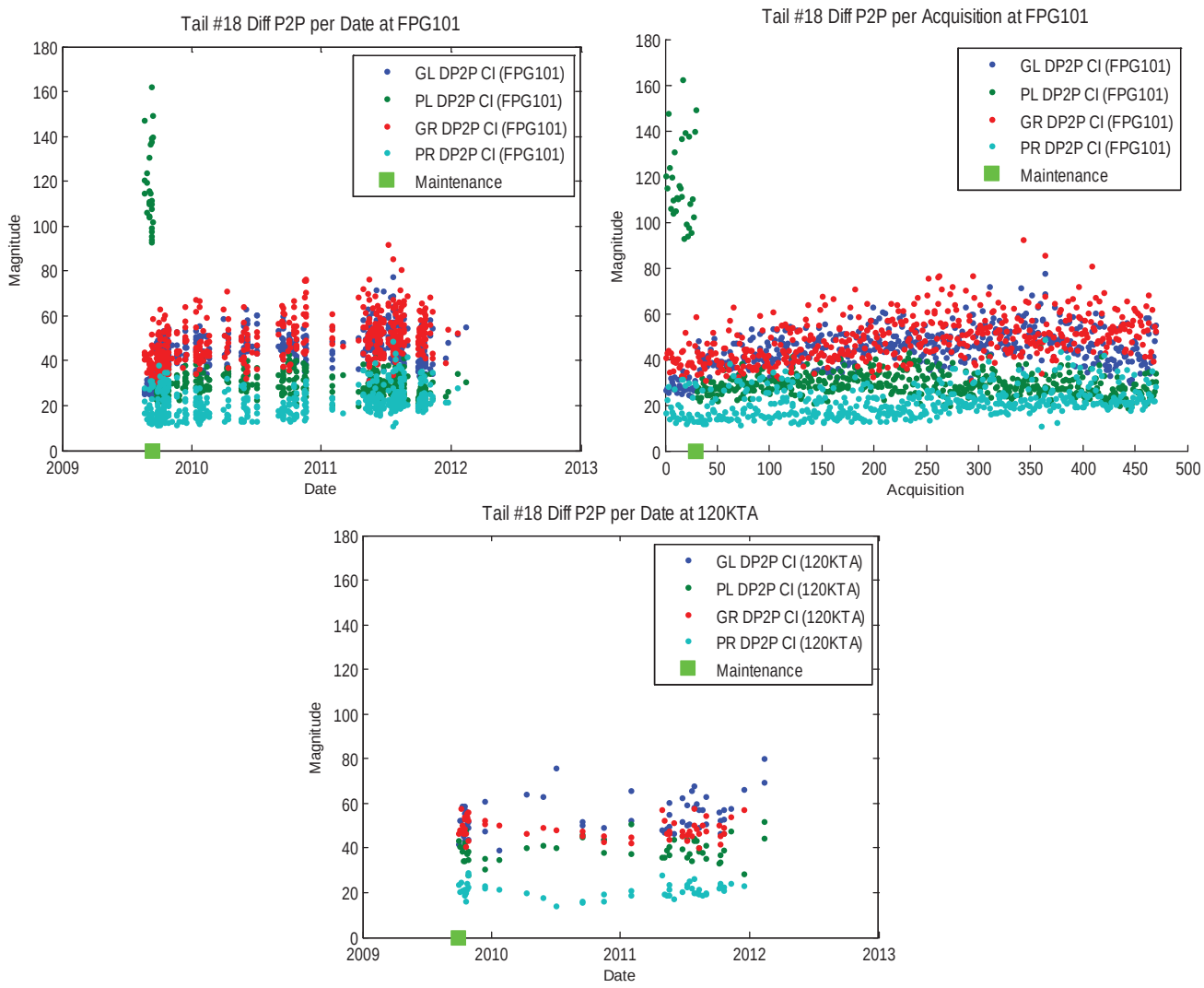

Figure 9.—Tail Number 18 Plots of DP2P per Date, Acquisition and Regime

TABLE 11.—D2P2 MEAN AND STANDARD DEVIATION FOR TAIL NUMBER 18

Location	CI Name	Status	Index Start	Index End	No. Points	Mean	STD
PR	DP2P	Before	1	29	29	19.76	6.61
PR	DP2P	After	30	488	458	21.55	6.20
GR	DP2P	Before	1	29	29	40.34	5.56
GR	DP2P	After	30	488	458	49.65	9.62
PL	DP2P	Before	1	29	29	117.59	18.23
PL	DP2P	After	30	488	458	29.25	4.65
GL	DP2P	Before	1	29	29	28.36	2.73
GL	DP2P	After	30	490	460	46.08	7.39

The CI data from the 20 tails without damage was not individually plotted. Instead, histograms of the CI data from all 20 tails and a matrix comparing all six CIs were plotted for the pinion and the gear at the FPG and 120KTA regimes. This data was also generated for the damaged cases to enable a visual comparison between the CI data for the damaged and undamaged cases at the two regimes. These plots are located in Appendix C, “CI Comparison for Damaged and Undamaged Cases.” A representative example of the data contained in the Appendix C will be reviewed for the output gear damaged and undamaged cases during the FPG regime.

Figure 10, Figure C.1.1 in Appendix C, contains histograms and gear CI data at the FPG regime using data from helicopters with undamaged components and helicopters with damaged components. The damaged component data set contains CI data before replacement only. The top plot, in green, is the data from the 20 tails without damage. The bottom plot, in red, is the plot of the tails with gear set damage. The histograms are shown in blue. The matrix of plots enables linear relationships between the CIs to be seen. These plots also provide a qualitative representation of the differences in CI values between the damaged and undamaged cases.

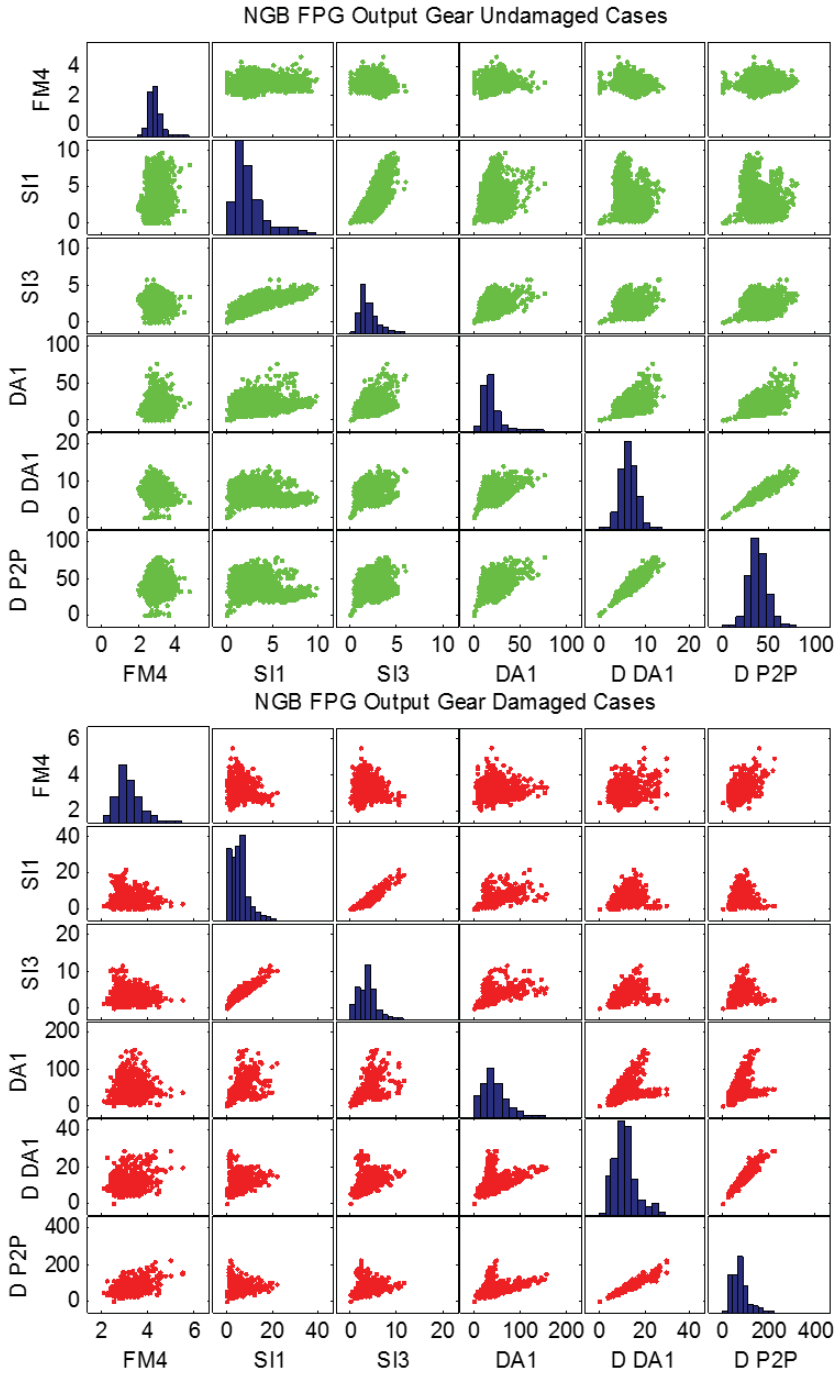

Figure 10.—Output Gear CI at FPG

Reviewing Appendix C, visual comparisons can be made between the CI data for the damaged and undamaged cases for both the FPG and 120KTA regimes. From these plots, several observations can be made for pinion and gear response for both regimes, for the undamaged and damaged cases. One is that the distributions are different for the damaged and undamaged cases. The other is that a linear relationship can be seen between SI1and SI3 and between DiffDA1 and DP2P. This is due to the similarity in the means these CIs are calculated.

Comparing undamaged to damaged cases, for both regimes, for the pinion CIs, overall magnitude was higher for the damaged cases for all CIs, except FM4. Comparing damaged cases only for both regimes, the CI magnitudes were comparable. Comparing undamaged cases only, DA1 values were slightly higher at 120KTA, while DiffDA1 and DP2P were higher at FPG.

Comparing undamaged to damaged cases, for the FPG regime, for the gear CIs, overall magnitude was higher for the damaged cases for all CIs. For the 120KTA regime, the overall magnitude was higher for the damaged cases for FM4, DiffDA1 and DP2P, but were comparable for SI1, SI3 and DA1. Comparing damaged cases only for both regimes, SI1 and SI3 were higher at FPG, while DiffDA1 and DP2P were higher at 120KTA. Comparing undamaged cases only, DA1, DiffDA1 and DP2P were higher at 120KTA.

Many factors affect the vibration response to gear and pinion tooth damage. These include fault type (gear or pinion), how the fault changes the signature response at mesh and the path the vibration response takes to get to the accelerometer. Per this qualitative assessment, it appears regime can also affect CI response to gear faults.

8.0 Discussion of Results

An initial assessment was made to evaluate the relationship between CI response to specific faulted components and regimes using the CI data from the baseline and damaged tails. Pearson Correlation Coefficients (r) were calculated to measure the strength and direction of the linear relationship between two parameters (Ref. 20). Correlation coefficients are calculated by dividing the covariance of the two variables (x, y) by the product of their standard deviations as shown in Equation (1) (Ref. 20).

$$r = \frac{n\sum xy - \left(\sum x\right)\left(\sum y\right)}{\sqrt{n\left(\sum x^2\right) - \left(\sum x\right)^2}\sqrt{n\left(\sum y^2\right) - \left(\sum y\right)^2}} \tag{1}$$

Its value ranges between –1 and +1. A perfect linear relationship between two parameters will have a correlation coefficient of 1 or –1. A value close to zero indicates no linear relationship between the two parameters. Hypothesis tests can be used to assess the significance of the relationship between the two parameters; however, a good rule of thumb is that values greater than 0.7 indicate a strong correlation and values less than 0.5 indicate a weak correlation.

A correlation matrix is generated for the entire dataset showing the linear relationship between the CIs to a damage state for the two regimes. To do this, CI data from the undamaged state and damaged state was paired with a damage parameter. This damage parameter was zero for the undamaged state and one for the damaged state. The correlation matrices for the output gear and the input pinion at the two regimes are shown in Figure 11 and Figure 12.

Figure 11 and Figure 12 provide plots and correlation coefficient for the combined undamaged and damaged tails at the two regimes. The strong linear relationship seen between SI1and SI3 and between DiffDA1 and DP2P in Figure 10, can also be seen and quantified in these plots with correlation coefficient values of 0.9 or greater. However, none of the correlation coefficient values between CIs and damage state exceeded 0.7. This is most likely due to the variance in the undamaged data set.

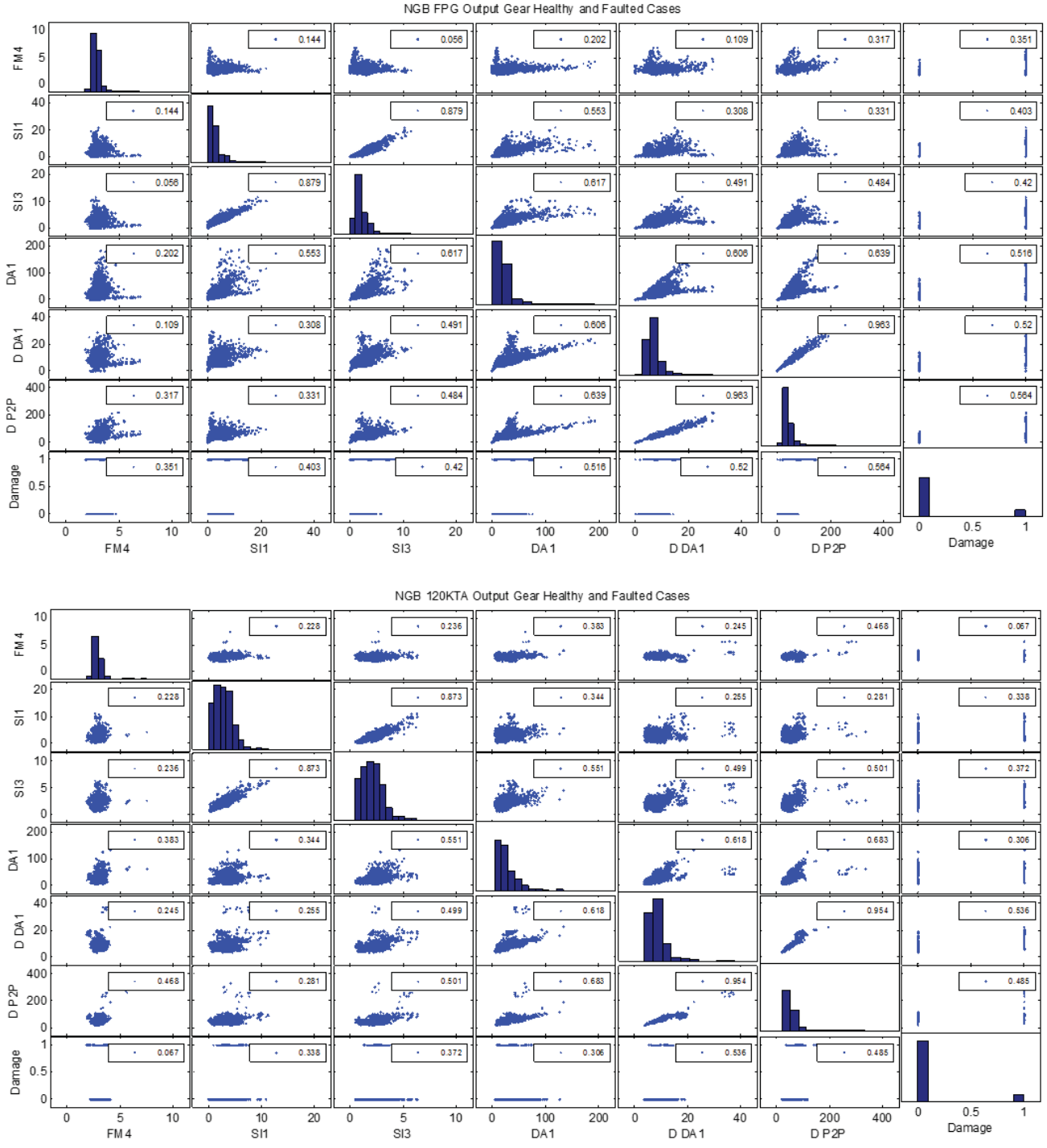

Figure 11.—Output Gear CI Correlation Matrix

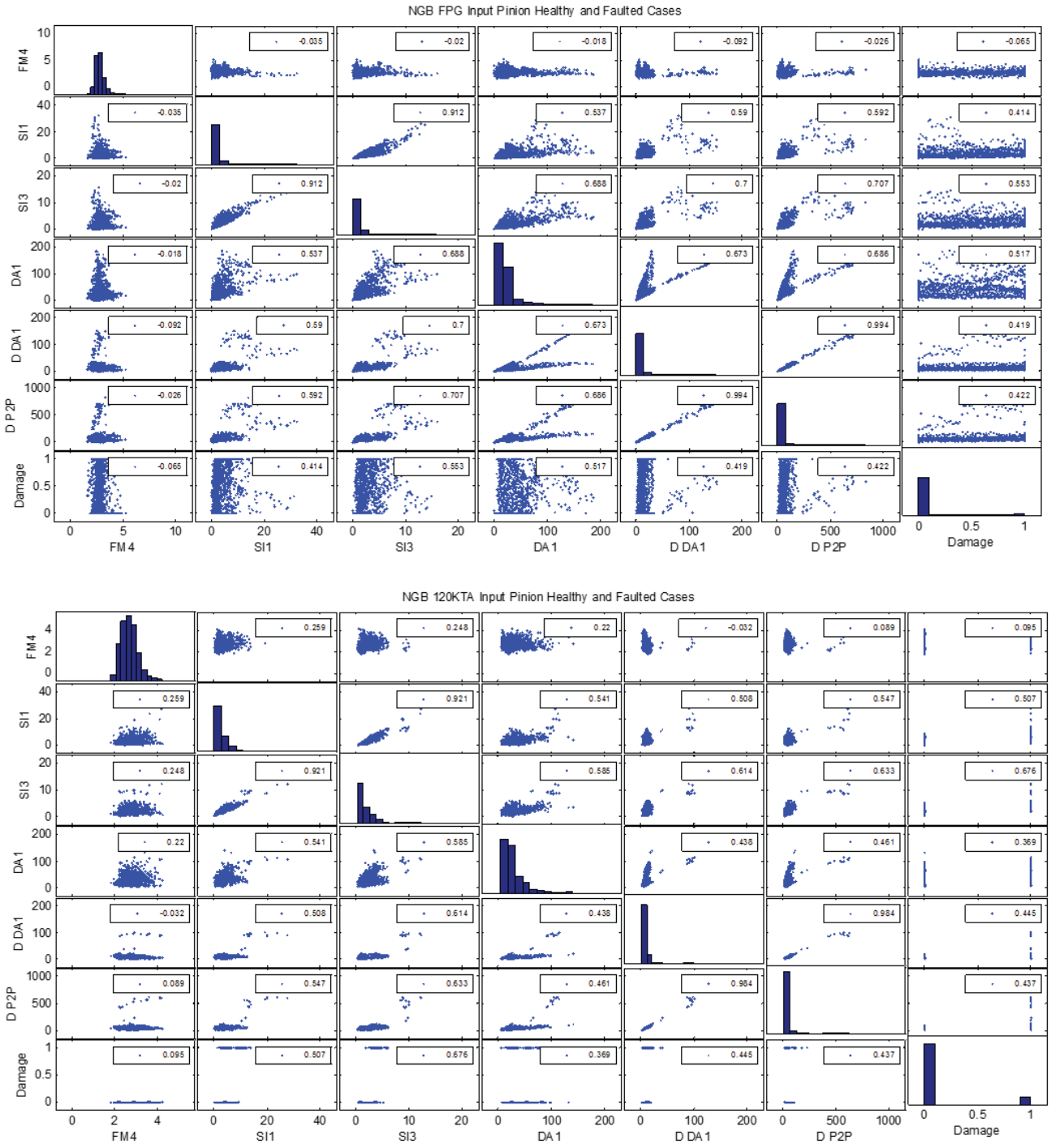

Figure 12.—Input Pinion CI Correlation Matrix

The next assessment of CI response to damage was only applied to the data from the tails with damage. For this method, CIs are analyzed per individual tail, not per fleet, crosses a discrete threshold prior to replacement and decreases to below the threshold after replacement. Table 12 summarizes the performance of the CIs for each tail to specific component faults. This table was generated from reviewing the summary of helicopters with spiral bevel gear tooth damage listed in Table 3, plots of CIs in Appendix A and CI statistical parameter tables in Appendix B. Similar to Table 3, tails with comparable failure modes and faulted components are color coded the same. Another column labeled "O" was added to this table. This represents other faulted components that were mentioned in the TDA in the same gearbox with the damaged gears. An "S" indicates spline wear or damage. An O indicates output bearing wear or damage. An "I" indicates input bearing wear or damage. The thresholds used to assess performance are listed as greater than or equal to a specific threshold. The cells highlighted in green indicate the CI of the damaged component responded to damage. The cells highlighted in blue indicate the meshing component responded. For example, for tail no. 13, the right gear was damaged but several right pinion CIs responded. The cells highlighted in light grey were unresponsive. The "*" indicates the CI responded during the 120KTA regime. If no "*" is shown, it indicates the CI measured during the FPG101 regime.

Note that the 120KTA regime data was not available for all tails before and after replacement. For tail no. 15, no 120KTA data was available for before and after replacement. For tails numbers 1, 7, and 18 not 120KTA data was available before replacement. The effect of regime on CI response could not be evaluated for these four tails. For tail no. 20, no 120KTA data was available after replacement.

TABLE 12.—SUMMARY OF CI RESPONSE

Tail no.	PR	GR	PL	GL	O	DA1 > 80	FM4 > 4.5	SI1 > 6	SI3 > 6	DiffDA1 > 15	DP2P > 80
1			x	x	S		GL			PL	PL
2			x	x						PL*	PL*,GL*
3			x	x	S,O						
4			x		O	PL,PL*,GL,GL*		PL,PL*,GL,GL*	PL	PL,GL,PL*	PL,PL*,GL,GL*
5			x		S			PL,PL*	PL*	PL,PL*	PL ,PL*
6	x							PR*	PR*	PR,GR*	PR,GR*
7	x	x					GR				GR
8	x	x			I			PR,PR*			
9	x	x			O						
10	x				O			GR*		PR*	PR*
11		x			O						
12	x	x									
13	x	x				PR,PR*	GR*	PR,PR*	PR,PR*	GR,GR*,PR,PR*	GR,GR*,PR,PR*
14			x	x		PL,PL*,GL,GL*		PL,PL*,GL,GL*	PL,PL*,GL,GL*	PL,PL*,GL,GL*	PL,PL*,GL,GL*
15			x	x		PL		PL	PL	PL	PL
16			x	x		PL,PL*,GL,GL*		GL,PL		PL,PL*,GL,GL*	PL,PL*,GL,GL*
17			x								
18			x				PL		PL	PL	PL
19	x	x									
20	x	x				GR,PR		GR,PR	GR	PR,PR*	PR,PR*

After reviewing the CI plots and statistical tables in Appendix A and Appendix B, a summary of each CI response to component failure modes is summarized below:

DA1 responded to damage for **six** tails: numbers 4, 13, 14, 15, 16 and 20.

- PL, PL*, GL and GL* responded to one tail (no. 4) with left pinion and output bearing damage and two tails (nos.14 and 16) with left gear and pinion damage and one tail (no. 4) with left pinion and output bearing damage.
- PL responded to one tail (no. 15) with left gear and pinion damage. This was the case of moderate wear to the gear and pinion teeth.
- PR and PR* responded to one tail (no. 13) with right pinion and gear damage. This was the case of the chipped gear tooth on the toe side.
- PR and GR responded to one tail (no. 20) with right gear and pinion damage.
- For several tails where the CI responded poorly, the CI value was monotonic.
- Since the FPG101 regime has a wide torque band, and this CI is known for its sensitivity to torque, this may be the cause of its poor performance.

FM4 responded to damage for **four** tails: numbers 1, 7, 13 and 18.

- GL responded to one tail (no. 1) with left pinion and gear damage and spline wear.
- GR responded to one tail (no. 7) with right pinion and gear damage.
- GR* responded to one tail (no. 13) with right gear and pinion damage.
- PL responded to one tail (no. 18) with left pinion damage.
- FM4 was not as responsive to damage as the other five CIs.

SI1 responded to damage for **10** tails: numbers 4, 5, 6, 8, 10, 13, 14, 15, 16, and 20.

- PL, PL*, GL and GL* responded to one tail (no. 4) with left pinion and output bearing damage.
- PL and PL* responded to one tail (no. 5) with left pinion and spline damage.
- PR* responded to one tail (no. 6) with right pinion damage.
- PR and PR* responded to one tail (no. 8) with right pinion and input bearing damage.
- GR* responded to one tail (no. 10) with right *pinion* and output bearing damage.
- PR and PR* responded to one tail (no. 13) with right pinion and gear damage.
- PL, PL*, GL and GL* responded to one tail (no. 14) with left pinion and gear damage.
- PL responded to one tail (no. 15) with left pinion and gear damage.
- PL and GL responded to one tail (no. 16) with left pinion and gear damage.
- PR and GR responded to one tail (no. 20) with right pinion and gear damage.
- For tails numbers 10 and 13, the meshing component CI responded to damage.

SI3 responded to damage for **eight** tails: numbers 4, 5, 6, 13, 14, 15, 18, and 20.

- PL responded to one tail (no. 4) with left pinion and output bearing damage.
- PL* responded to one tail (no. 5) with left pinion and spline damage.
- PR* responded to one tail (no. 6) with right pinion damage.
- PR* responded to one tail (no. 13) with right pinion and gear damage.
- PL, PL*, GL and GL* responded to one tail (no. 14) with left pinion and gear damage.
- PL responded to one tail (no. 15) with left pinion and gear damage.
- PL responded to one tail (no. 18) with left pinion damage.

- GR responded to one tail (no. 20) with right pinion and gear damage.
- The pinion CIs were more response to different regimes than the gear CIs.

DiffDA1 responded to damage for **12** tails: numbers 1, 2, 4, 5, 6, 10, 13, 14, 15, 16, 18, and 20.

- PL responded to one tail (no. 1) with left pinion and gear damage and spline wear.
- PL* responded to one tail (no. 2) with left pinion and gear damage.
- PL, PL* and GL responded to one tail (no. 4) with left pinion and output bearing damage.
- PL and PL* responded to one tail (no. 5) with left pinion and spline damage.
- PR and GR* responded to one tail (no. 6) with right pinion damage.
- PR* responded to one tail (no. 10) with right *pinion* and output bearing damage.
- PR, PR*, GR and GR* responded to one tail (no. 13) with right pinion and gear damage.
- PL, PL* GL and GL* responded to one tail (no. 14) with left pinion and gear damage.
- PL responded to one tail (no. 15) with left pinion and gear damage.
- PL, PL*, GL and GL* responded to one tail (no. 16) with left pinion and gear damage.
- PL responded to one tail (no. 18) with left pinion damage.
- PR and PR* responded to one tail (no. 20) with right pinion and gear damage.

DP2P responded to damage for **13** tails: numbers 1, 2, 4, 5, 6, 7, 10, 13, 14, 15, 16, 18, and 20.

- PL responded to one tail (no. 1) with left pinion and gear damage and spline wear.
- PL* and GL* responded to one tail (no. 2) with left pinion and gear damage.
- PL, PL*, GL and GL* responded to one tail (no. 4) with left pinion and output bearing damage.
- PL and PL* responded to one tail (no. 5) with left pinion and spline damage.
- PR and GR* responded to one tail (no. 6) with right pinion damage.
- GR responded to one tail (no. 7) with right pinion and gear damage.
- PR* responded to one tail (no. 10) with right *pinion* and output bearing damage.
- PR, PR*, GR and GR* responded to one tail (no. 13) with right pinion and gear damage.
- PL, PL* GL and GL* responded to one tail (no. 14) with left pinion and gear damage.
- PL responded to one tail (no. 15) with left pinion and gear damage.
- PL, PL*, GL and GL* responded to one tail (no. 16) with left pinion and gear damage.
- PL responded to one tail (no. 18) with left pinion damage.
- PR and PR* responded to one tail (no. 20) with right pinion and gear damage.

Based on the review of the six CIs for the four components, DP2P responded the best to varying levels of damage on thirteen of the fourteen helicopters evaluated. This CI was not available in the onboard MSPU HUMS during occurrences of damage. It was also not available during damage progression tests in the test rig MSPU HUMS (Ref. 7).

DiffDA1 responded to varying levels of damage on 12 helicopters and SI1 responded to ten of the fourteen helicopters evaluated. These two CIs were also not available in the onboard MSPU HUMS during occurrences of damage. They were also not available during damage progression tests in the test rig MSPU HUMS. Note that SI1 was the only CI that responded to right pinion damage on helicopter number 8. This was also the only helicopter with right input bearing damage prior to replacement.

Of the three CIs currently available in the MSPU, DA1, FM4 and SI3, SI3, responded to eight, DA1 responded to six and FM4 responded to four of the 14 helicopters evaluated. FM4, the poorest performing CI, was not as responsive to damage as the other five CIs. Conversely, when compared to the other two, it

was the only CI that responded to right gear and pinion damage on helicopter no. 7 and left gear and pinion damage on helicopter no. 1.

For tail no. 8, only one CI, SI1, indicated damage to the right pinion. This type of damage was described as pinion teeth scuffing. However, CI response could not be correlated to the different failure modes described in the TDA. Since limited pictures were available and the description was subjective to the interpretation of the person performing the inspection, this analysis was inconclusive. In some cases, the CI of the component meshing with the damaged component responded.

Some CIs responded better at 120KTA regime instead of FPG101 regime. For tail no. 10, the only CIs at the 120KTA regime indicated damage to the right pinion. This may be due to the different torque bands used for each regime. Due to the wide torque band for each regime, more studies are required to determine their sensitivity to the changes within this band.

9.0 Summary

Helicopter health monitoring data from 40 helicopters, 20 with no known anomalies and 20 with spiral bevel gear damage, was processed with the same techniques applied to spiral bevel rig test data. Vibration-based gear condition indicators data was available when damage occurred and after the gear sets were replaced. Three onboard gear condition indicators were evaluated at two helicopter regimes. These included Figure of Merit 4 (FM4), Root Mean Square (RMS) or DA1 and ± 3 Sideband Index (SI3). Three additional condition indicators, not currently calculated onboard, were calculated from the archived data. These three were ± 1 Sideband Index (SI1), the DA1 of the difference signal (DiffDA1) and the peak-to-peak of the difference signal (DP2P).

Results found DP2P, performed the best, responding to varying levels of damage on 13 of the 14 helicopters evaluated. DiffDA1and SI1 also performed well responding to 12 and 10 of the 14 helicopters evaluated. Of the three CIs currently available in the MSPU, DA1, FM4 and SI3, SI3, responded to eight, DA1 responded to six and FM4 responded to four of the 14 helicopters evaluated. FM4, the poorest performing CI, was not as responsive to damage as the other five CIs. Conversely, when compared to the other two, it was the only CI that responded to damage on two helicopters. Regime did affect CI response to some gear faults.

Results from the analysis of the helicopter data, published in this report, and the rig data published in Reference 7 will be combined into a third report titled, “Investigation of Spiral Bevel Gear Condition Indicator Validation Via AC–29–2C. In the third, and final, report, test rig damage progression data will be compared to fielded rotorcraft. Observations, findings and lessons learned using subscale rig failure progression tests to validate helicopter gear condition indicators will be discussed.

Appendix A.—Plots of MSPU Condition Indicators from Damaged Tails

A.1 Tail Number 1

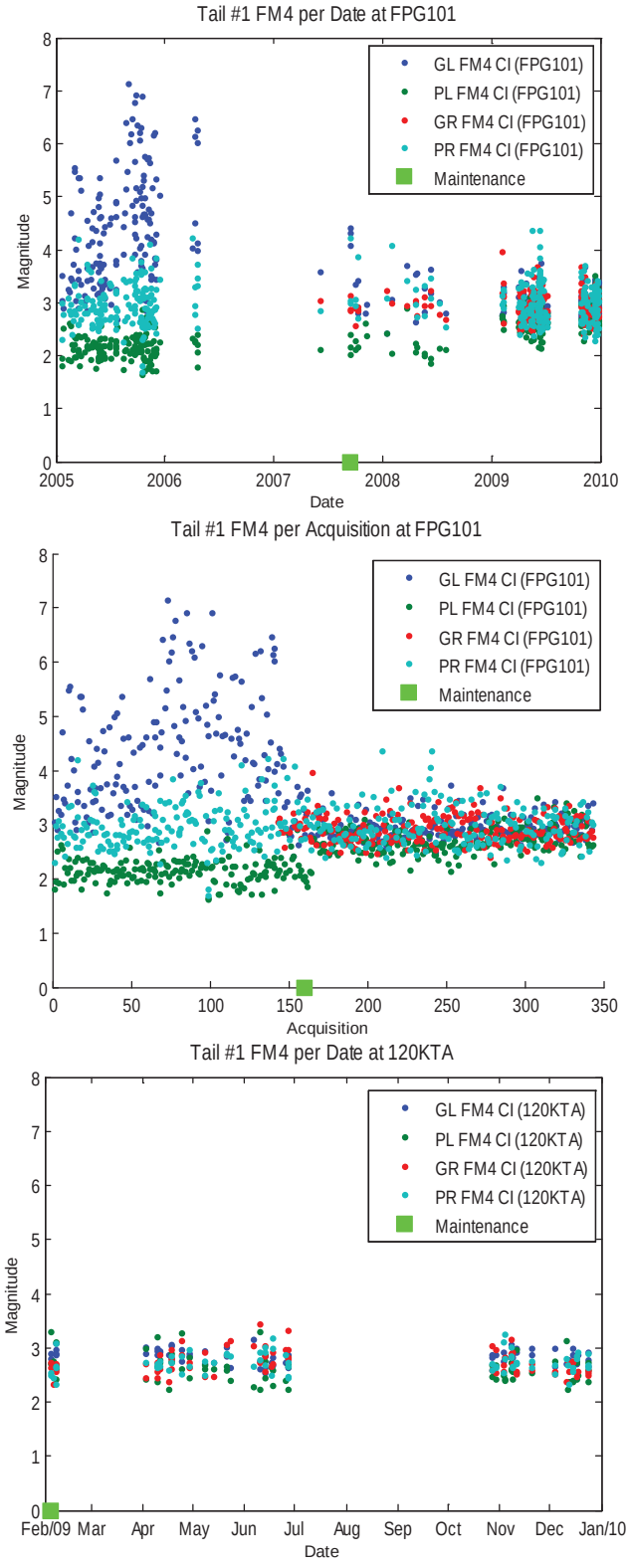

Figure A.1.1.—Tail Number 1 Plots of FM4 per Date, Acquisition and Regime

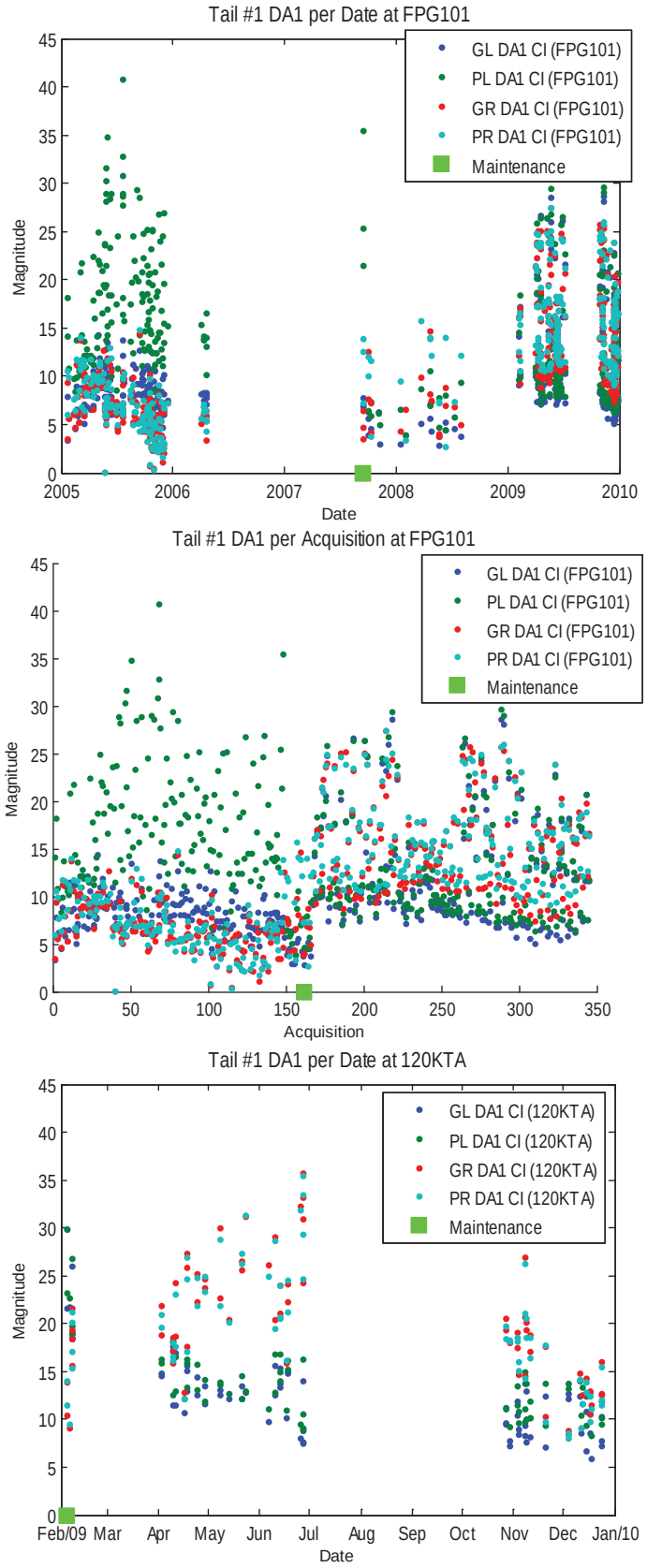

Figure A.1.2.—Tail Number 1 Plots of DA1 per Date, Acquisition and Regime

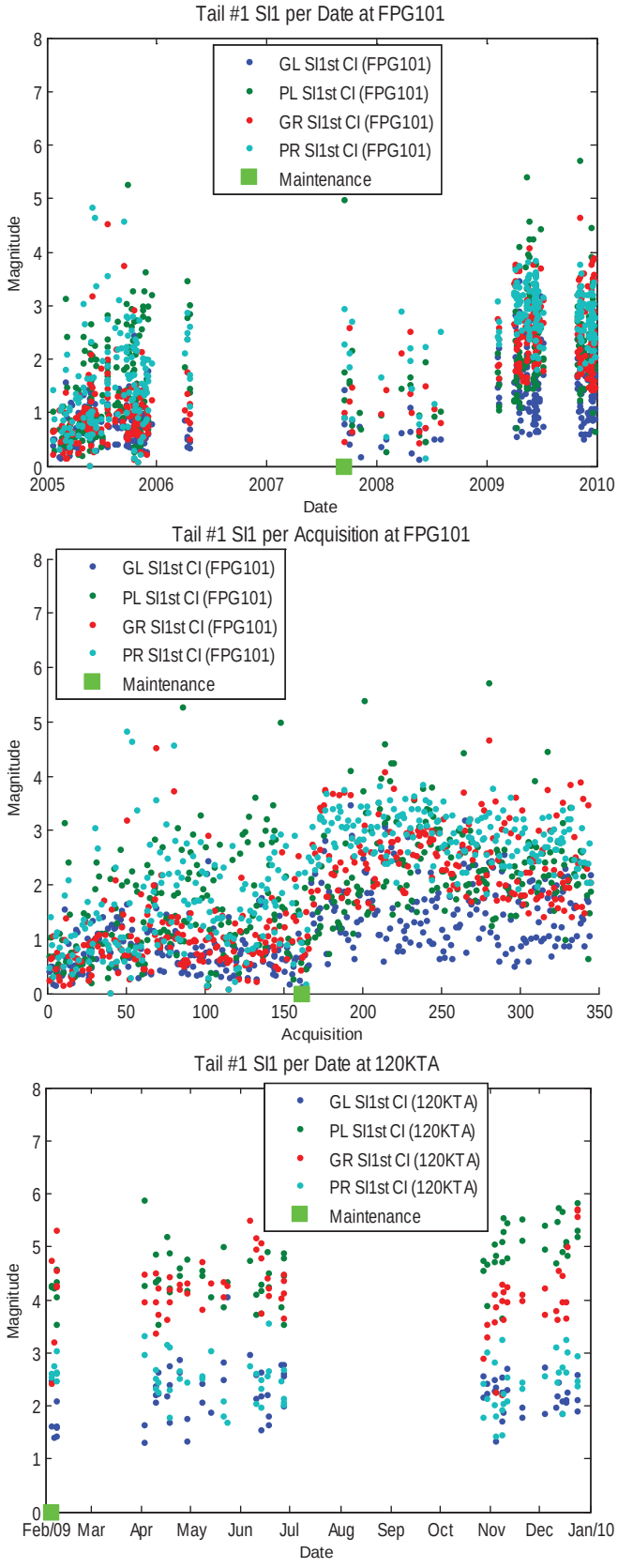

Figure A.1.3.—Tail Number 1 Plots of SI1 per Date, Acquisition and Regime

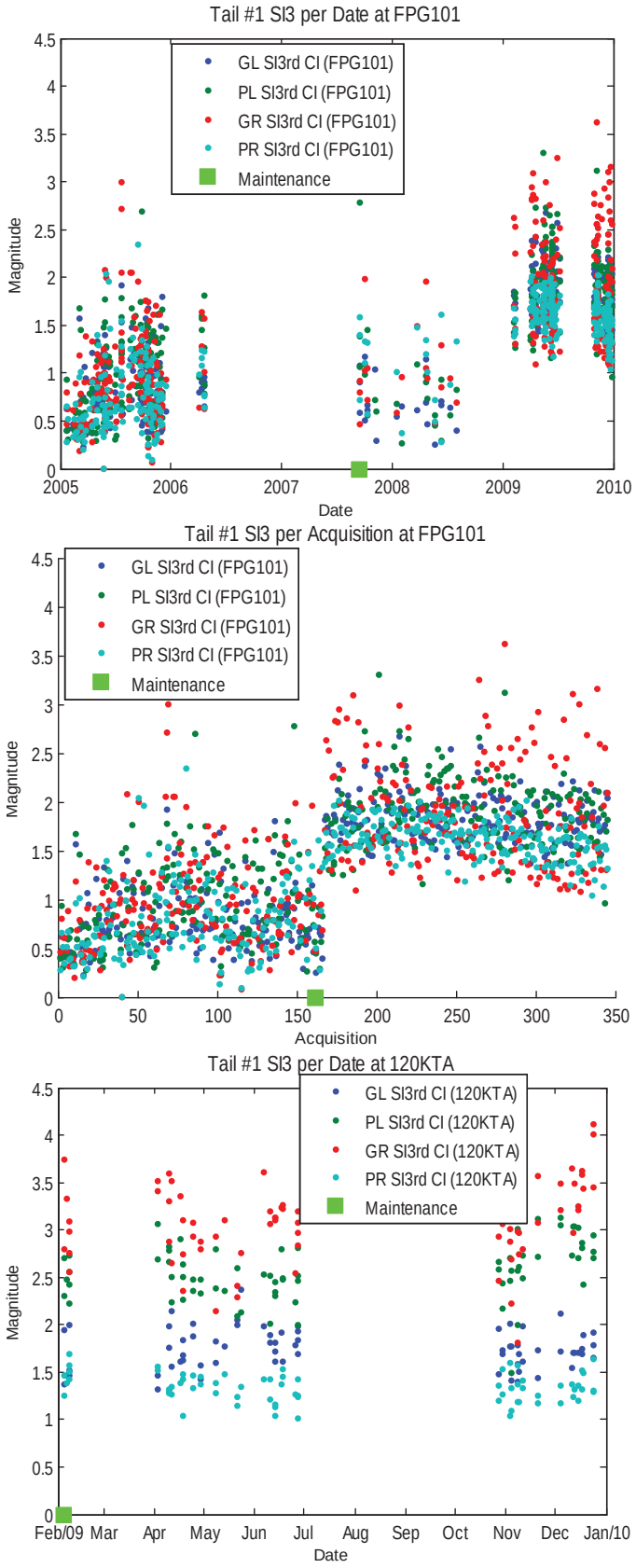

Figure A.1.4.—Tail Number 1 Plots of SI3 per Date, Acquisition and Regime

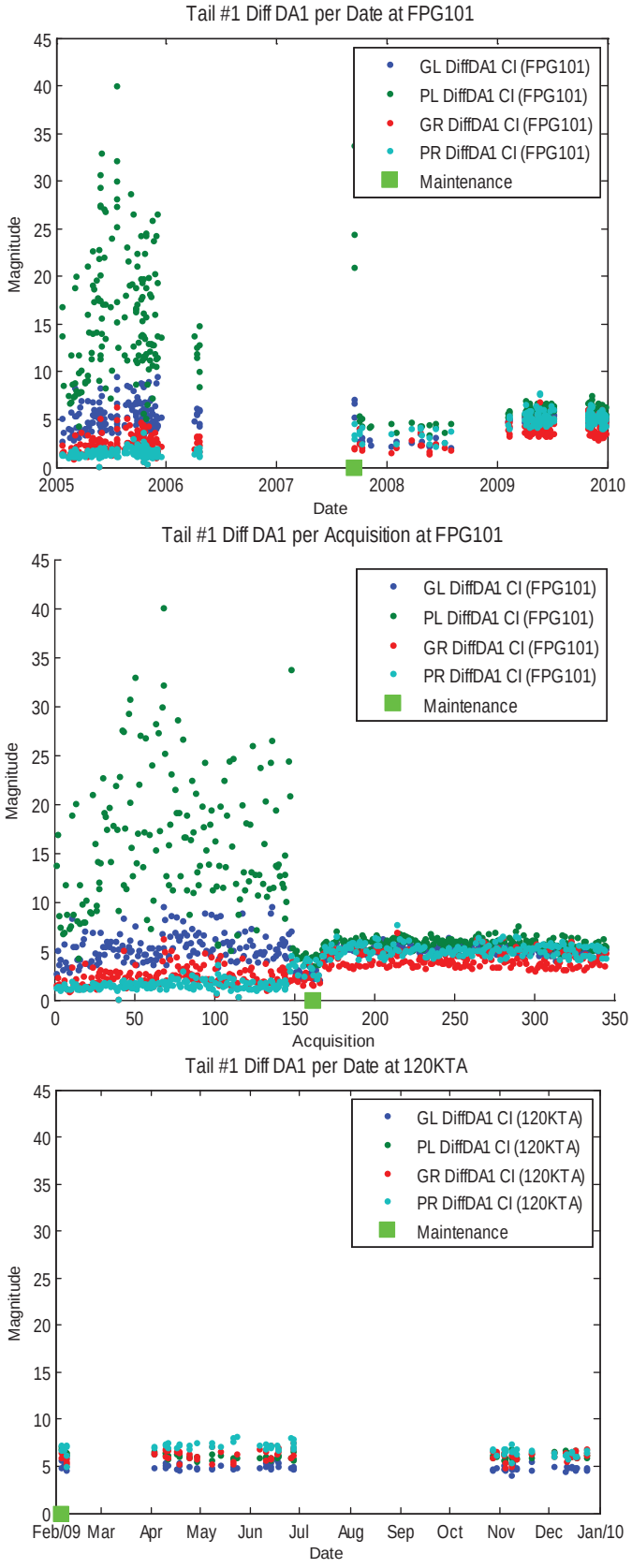

Figure A.1.5.—Tail Number 1 Plots of DiffDA1 per Date, Acquisition and Regime

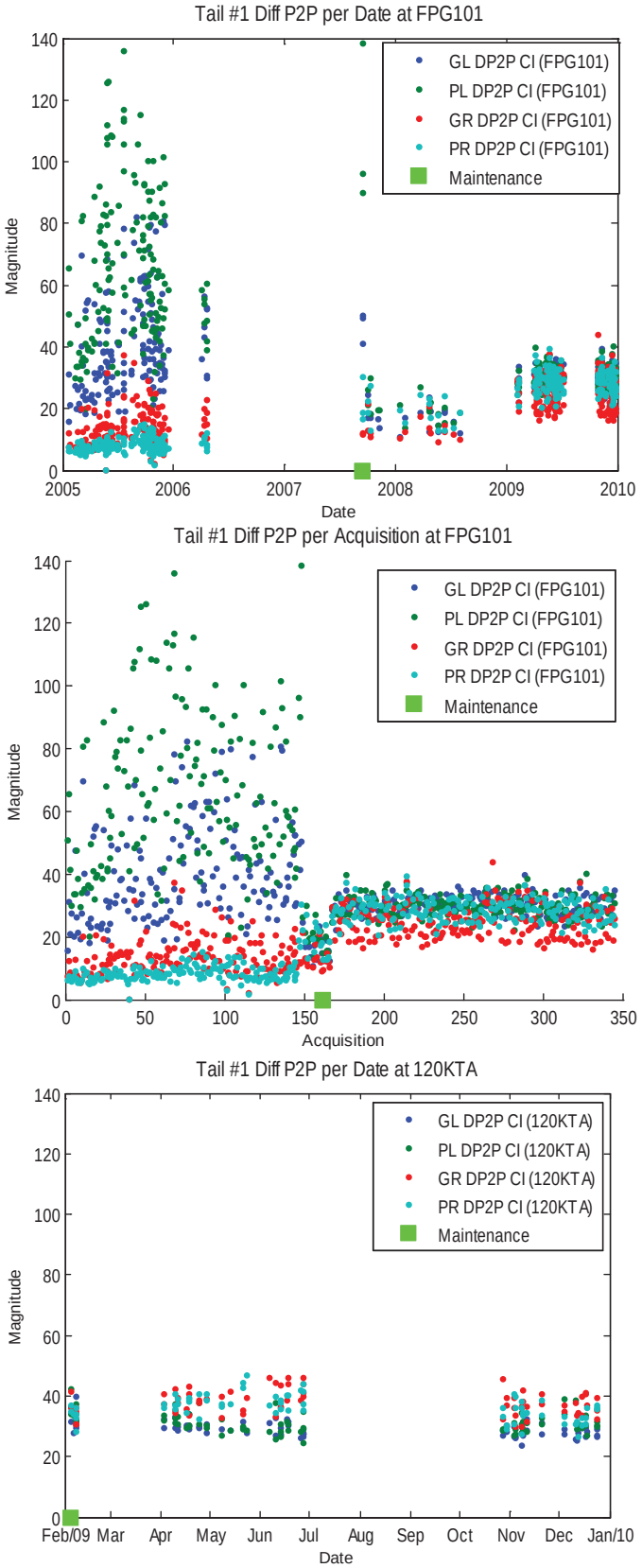

Figure A.1.6.—Tail Number 1 Plots of DP2P per Date, Acquisition and Regime

A.2 Tail Number 2

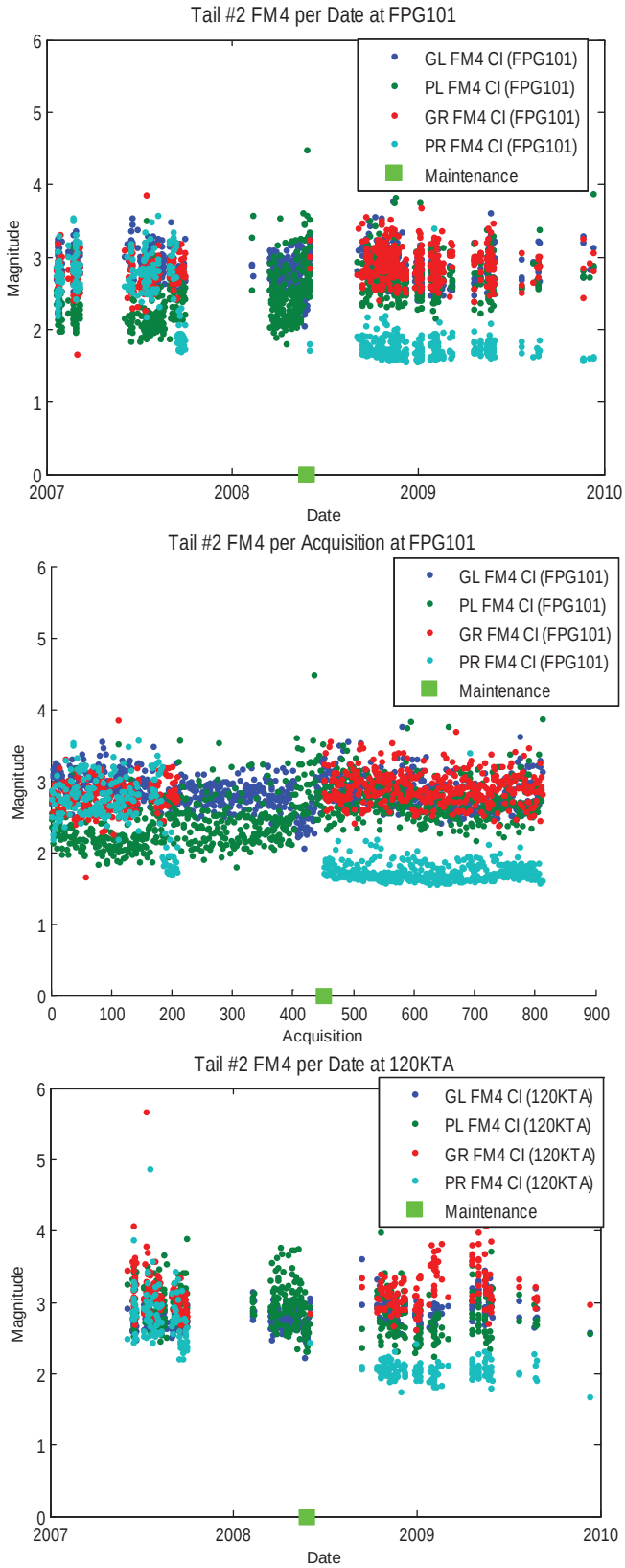

Figure A.2.1.—Tail Number 2 Plots of FM4 per Date, Acquisition and Regime

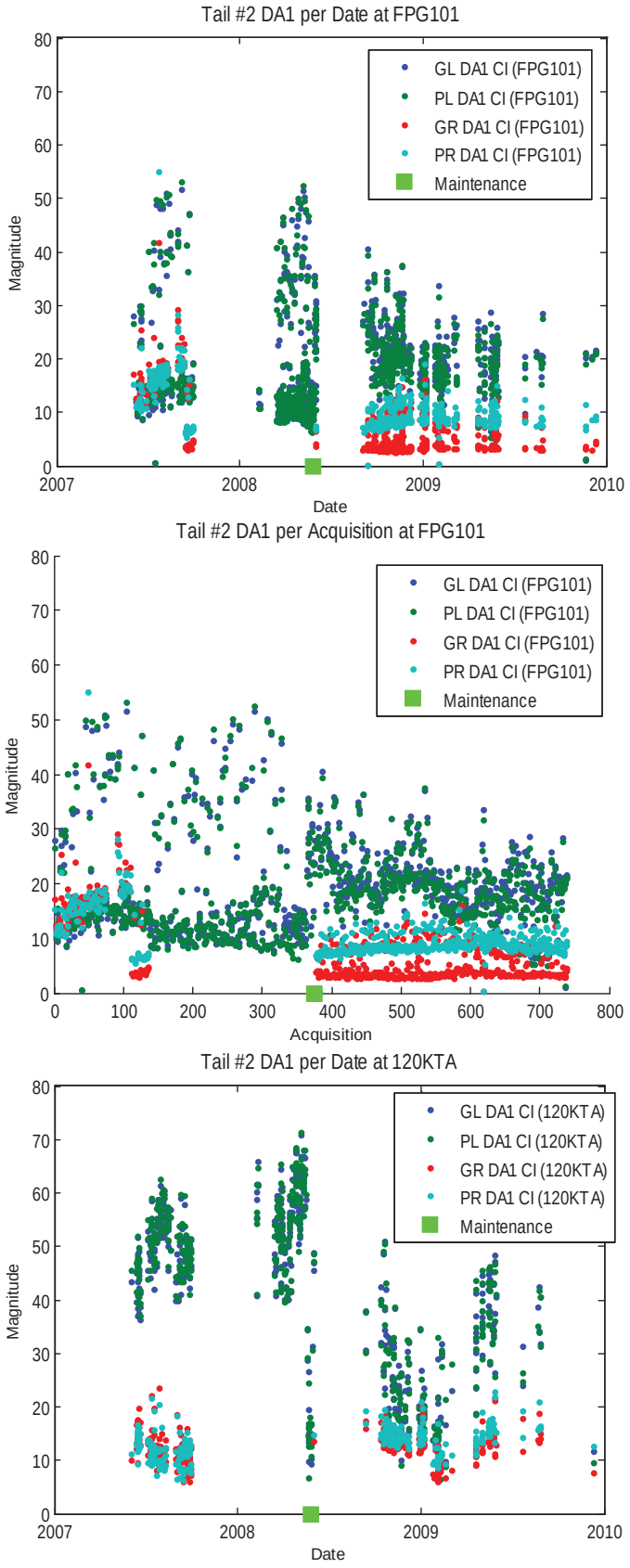

Figure A.2.2.—Tail Number 2 Plots of DA1 per Date, Acquisition and Regime

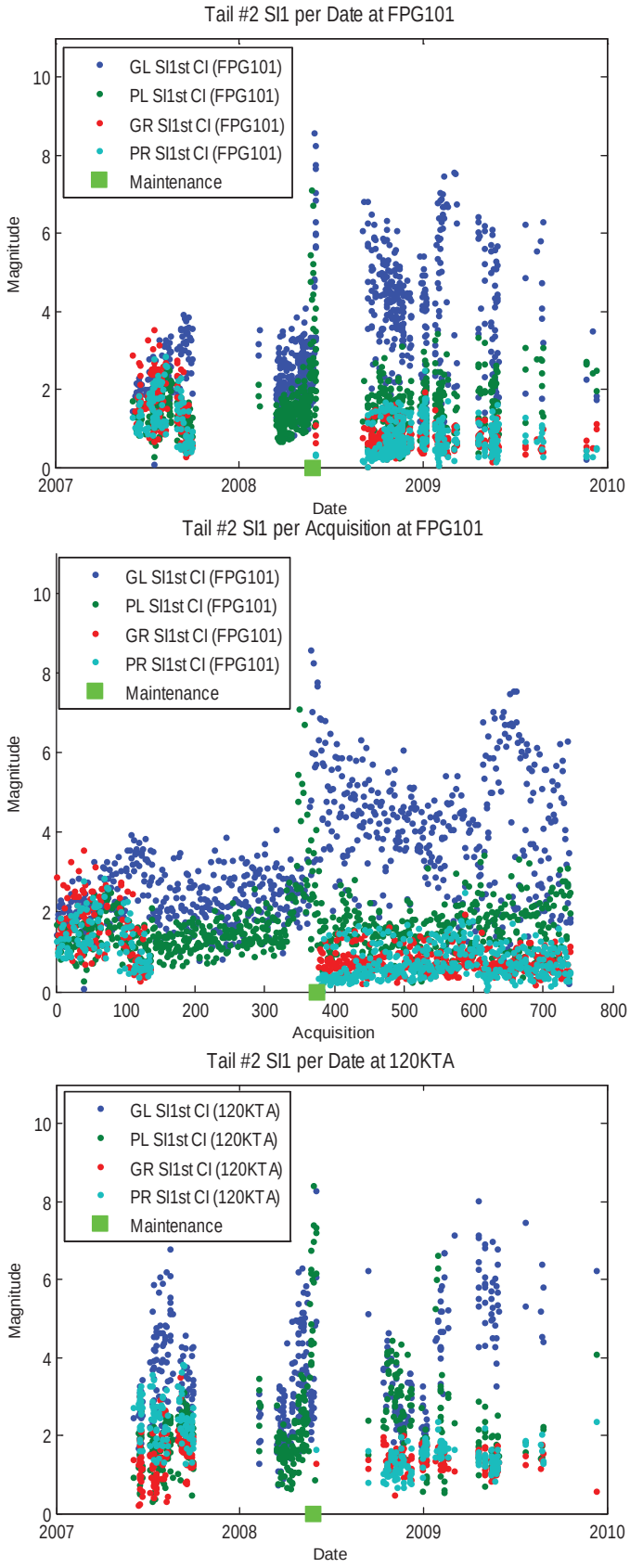

Figure A.2.3.—Tail Number 2 Plots of SI1 per Date, Acquisition and Regime

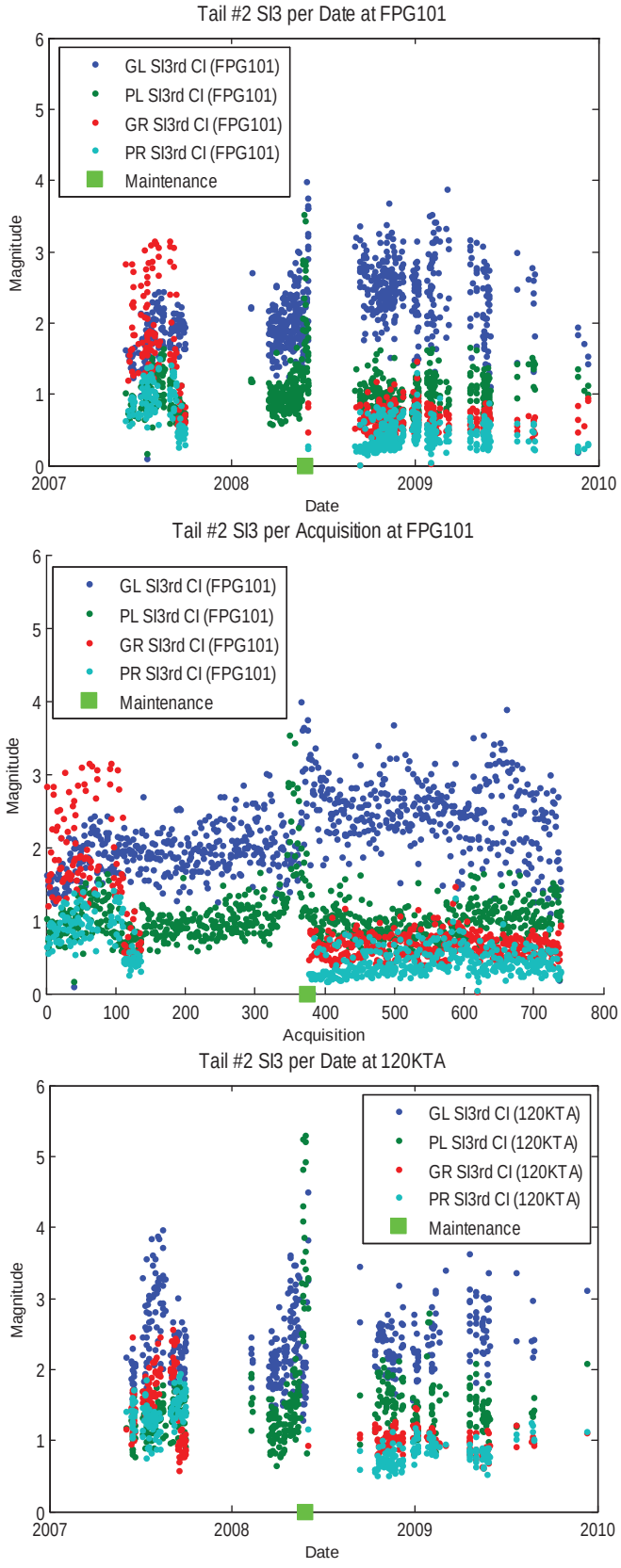

Figure A.2.4.—Tail Number 2 Plots of SI3 per Date, Acquisition and Regime

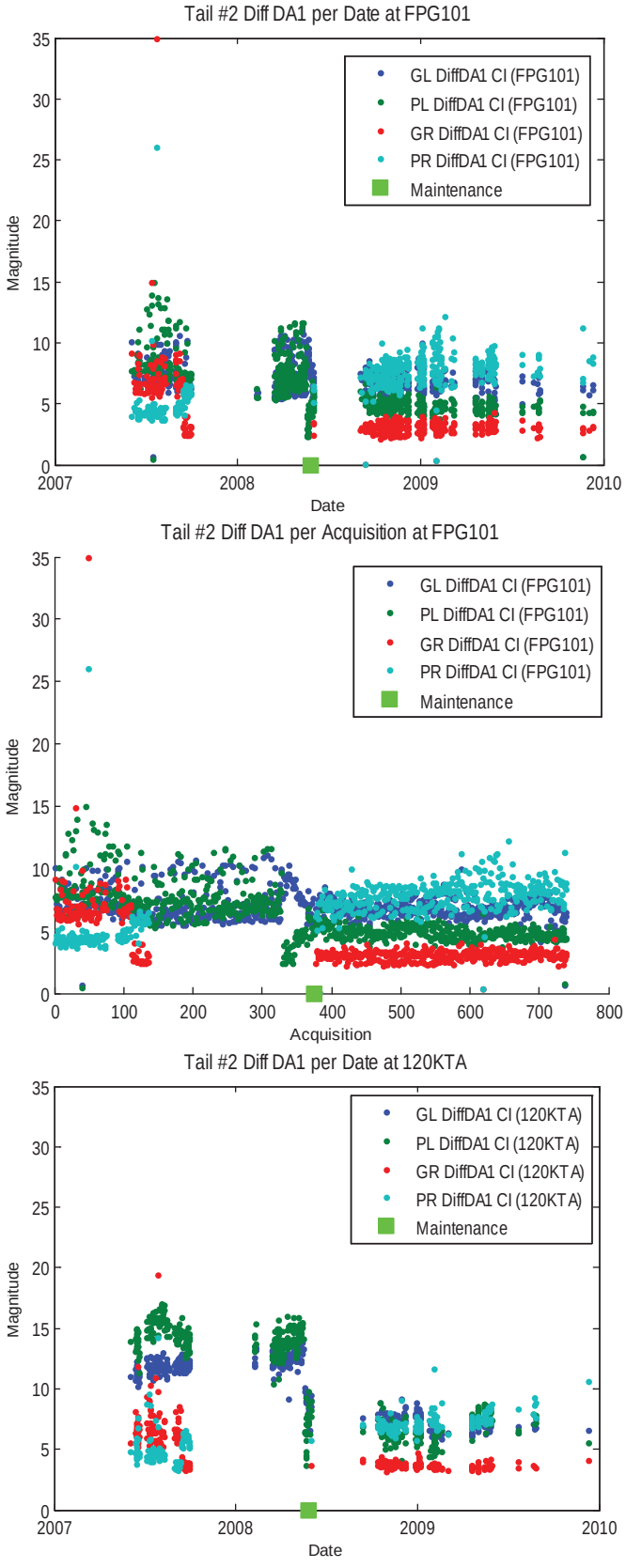

Figure A.2.5.—Tail Number 2 Plots of DiffDA1 per Date, Acquisition and Regime

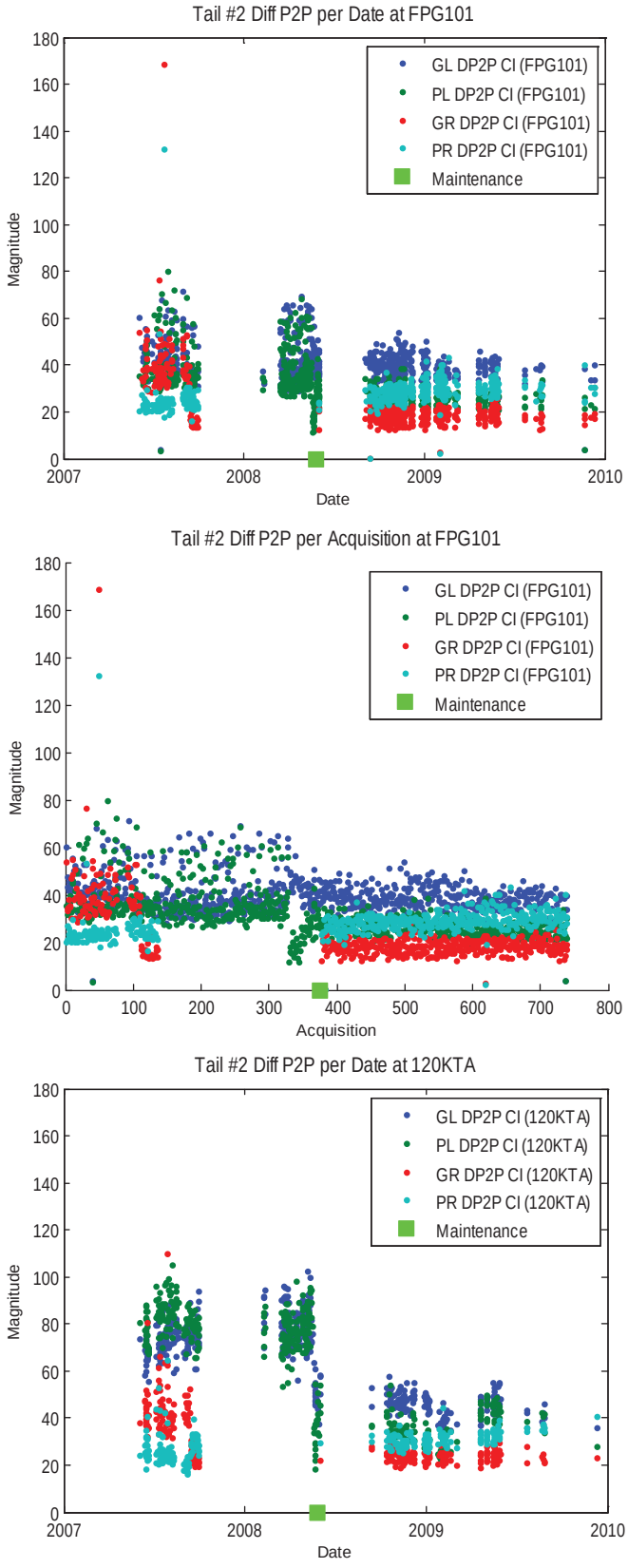

Figure A.2.6.—Tail Number 2 Plots of D2P2 per Date, Acquisition and Regime

A.3 Tail Number 3

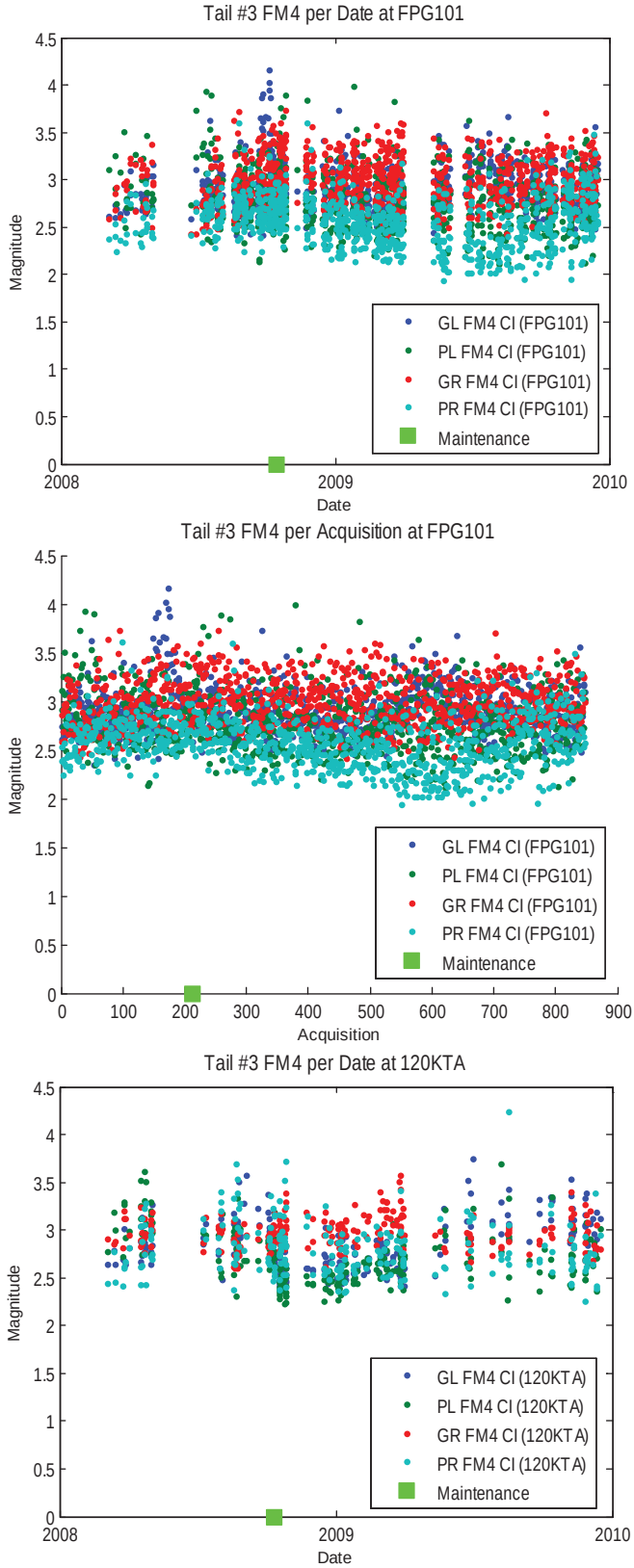

Figure A.3.1.—Tail Number 3 Plots of FM4 per Date, Acquisition and Regime

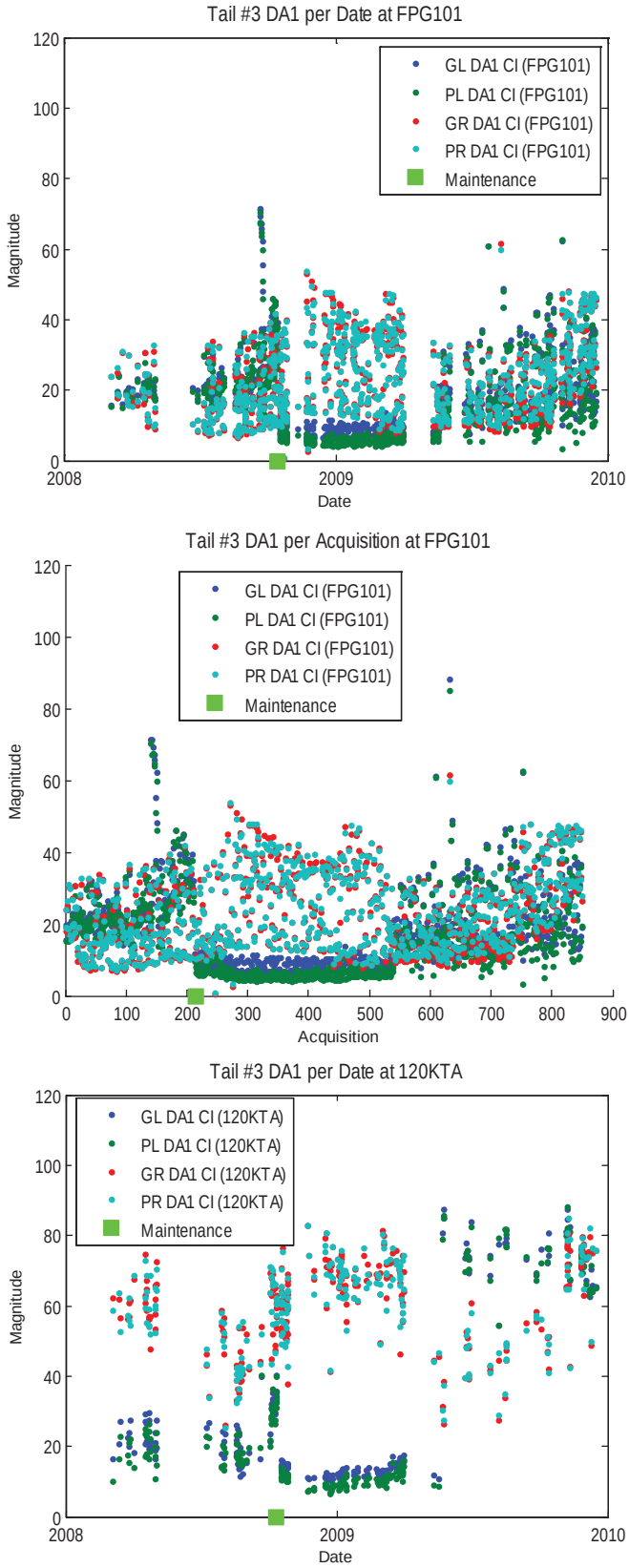

Figure A.3.2.—Tail Number 3 Plots of DA1 per Date, Acquisition and Regime

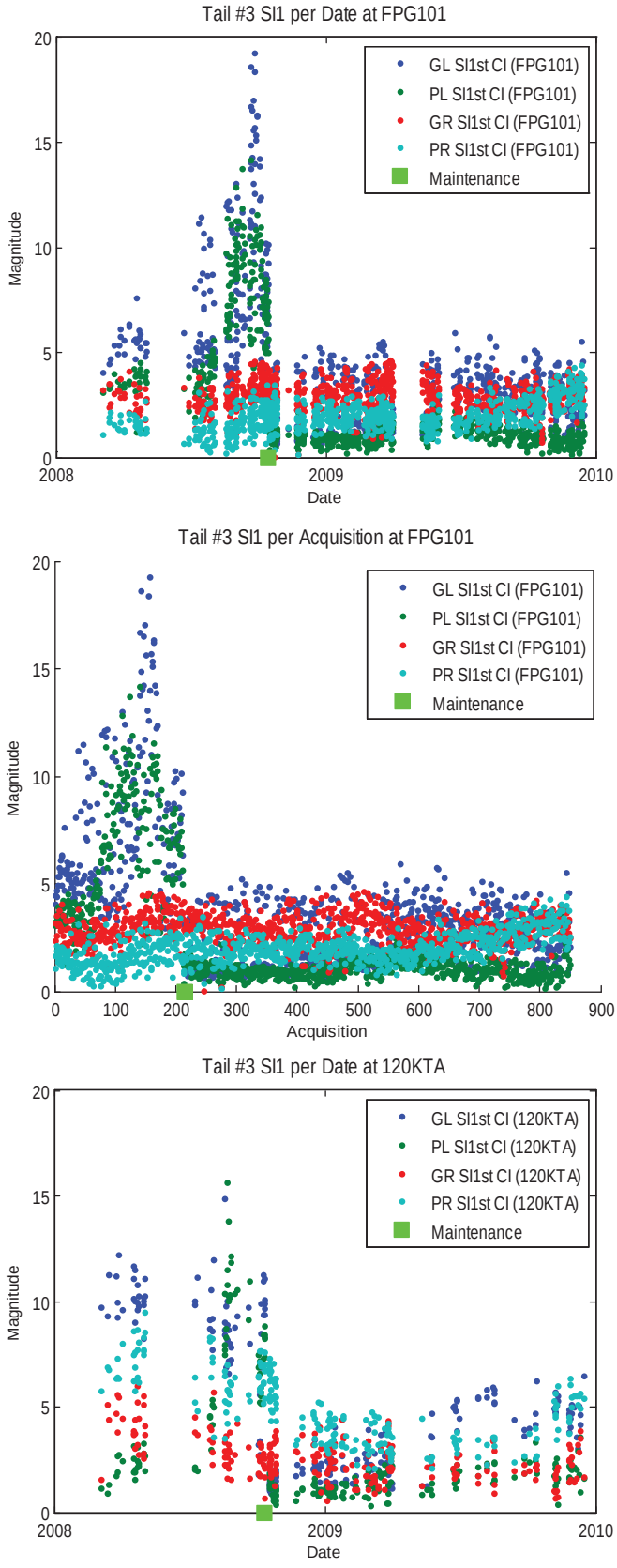

Figure A.3.3.—Tail Number 3 Plots of SI1 per Date, Acquisition and Regime

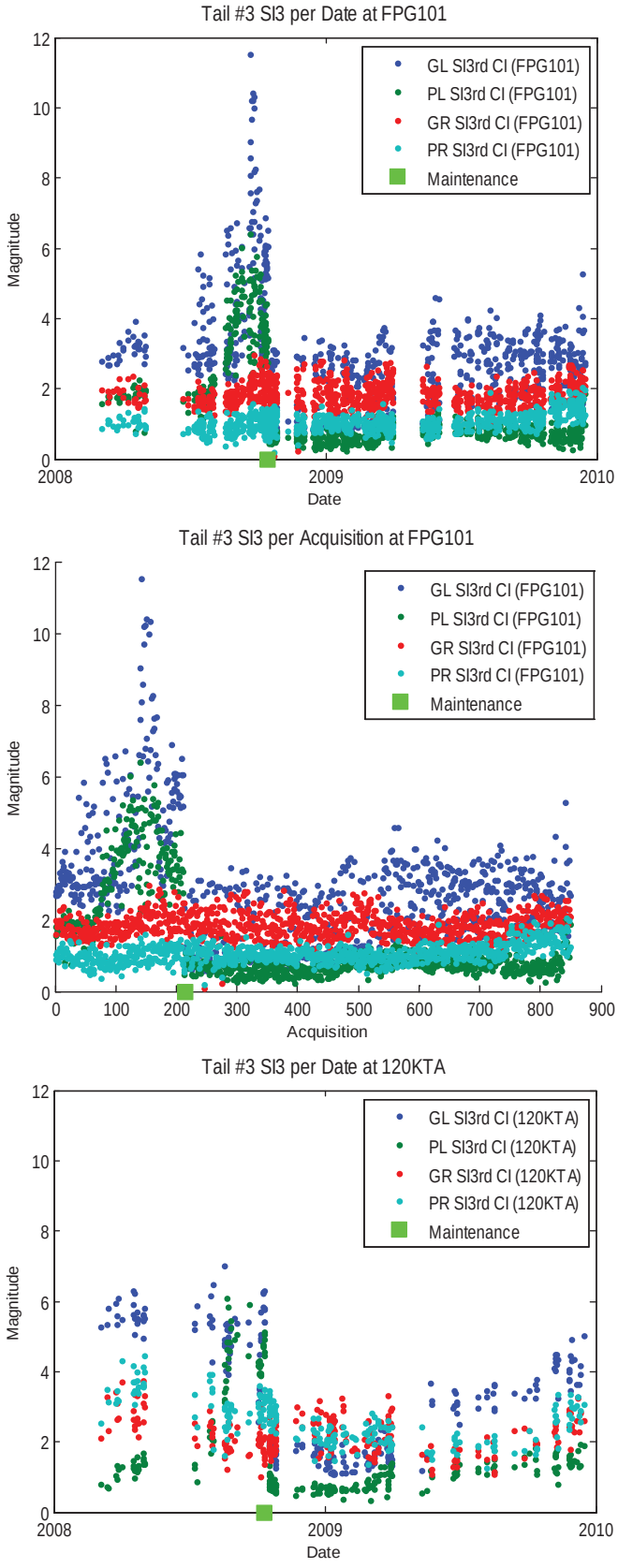

Figure A.3.4.—Tail Number 3 Plots of SI3 per Date, Acquisition and Regime

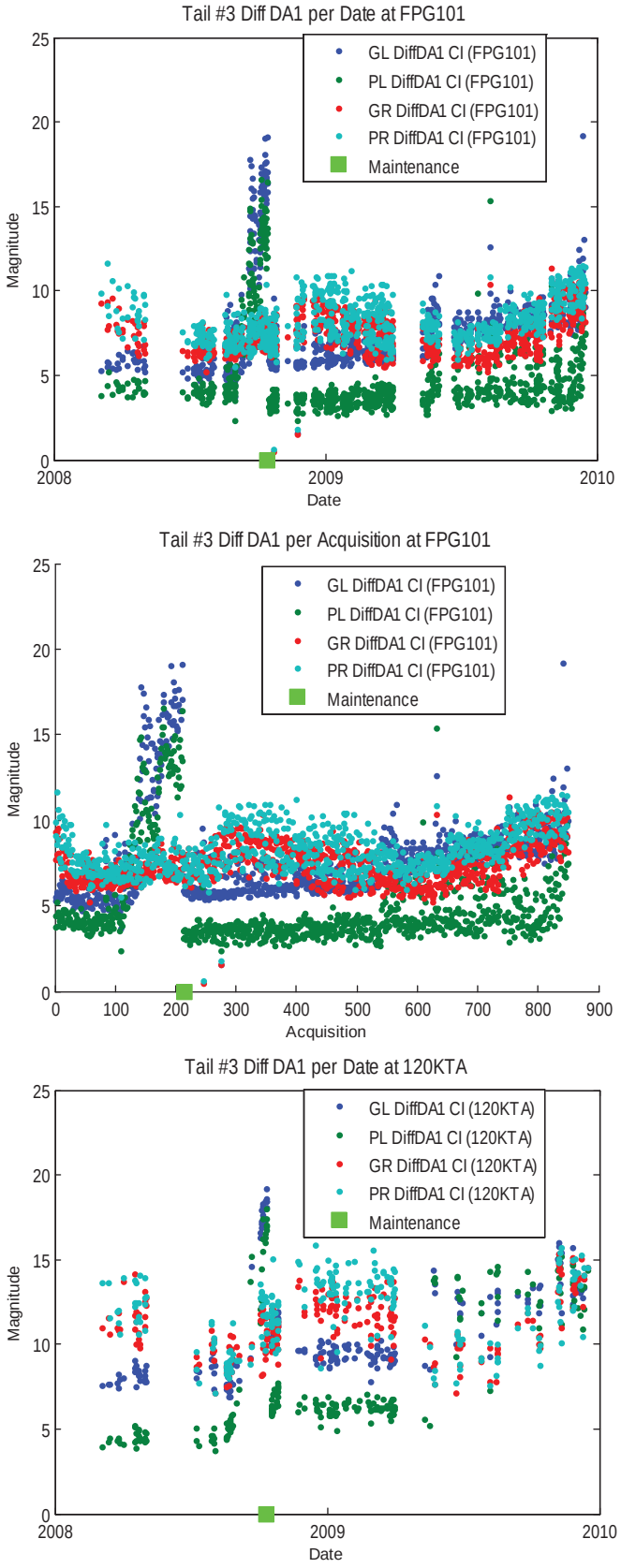

Figure A.3.5.—Tail Number 3 Plots of DiffDA1 per Date, Acquisition and Regime

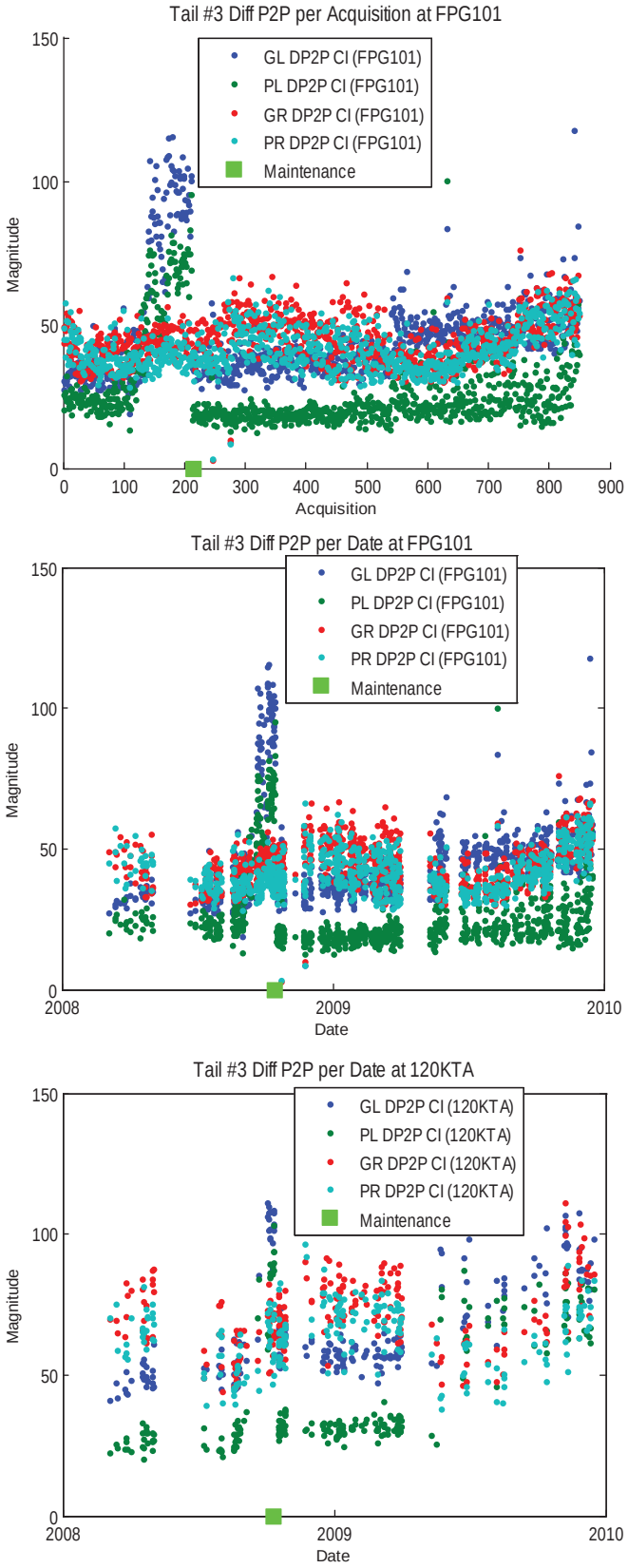

Figure A.3.6.—Tail Number 3 Plots of DP2P per Date, Acquisition and Regime

A.4 Tail Number 4

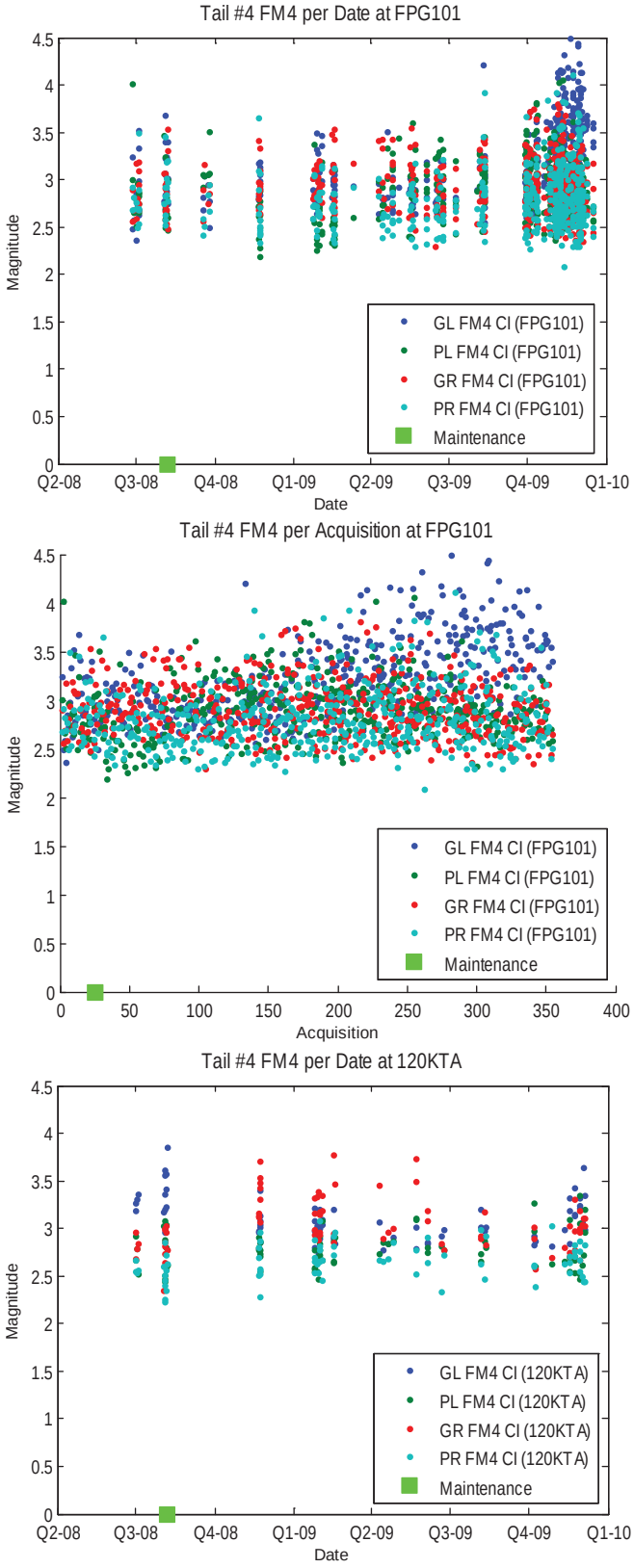

Figure A.4.1.—Tail Number 4 Plots of FM4 per Date, Acquisition and Regime

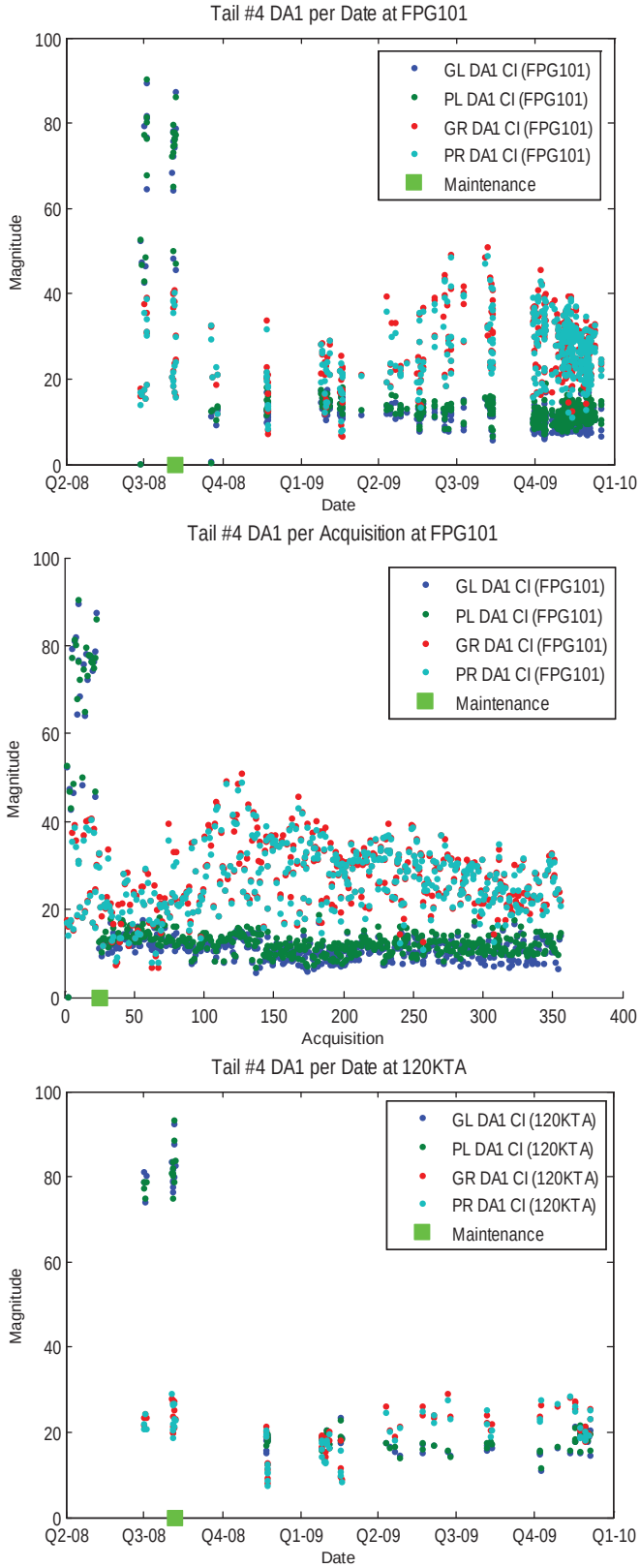

Figure A.4.2.—Tail Number 4 Plots of DA1 per Date, Acquisition and Regime

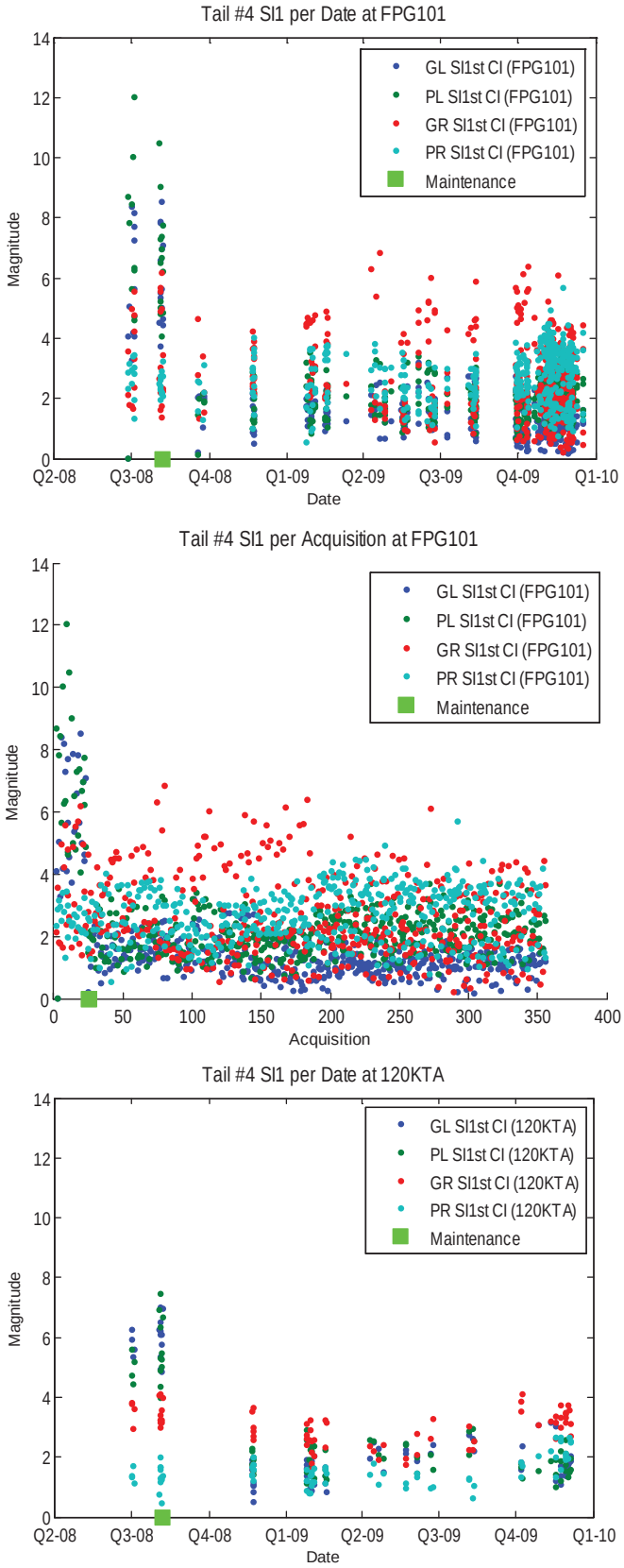

Figure A.4.3.—Tail Number 4 Plots of SI1 per Date, Acquisition and Regime

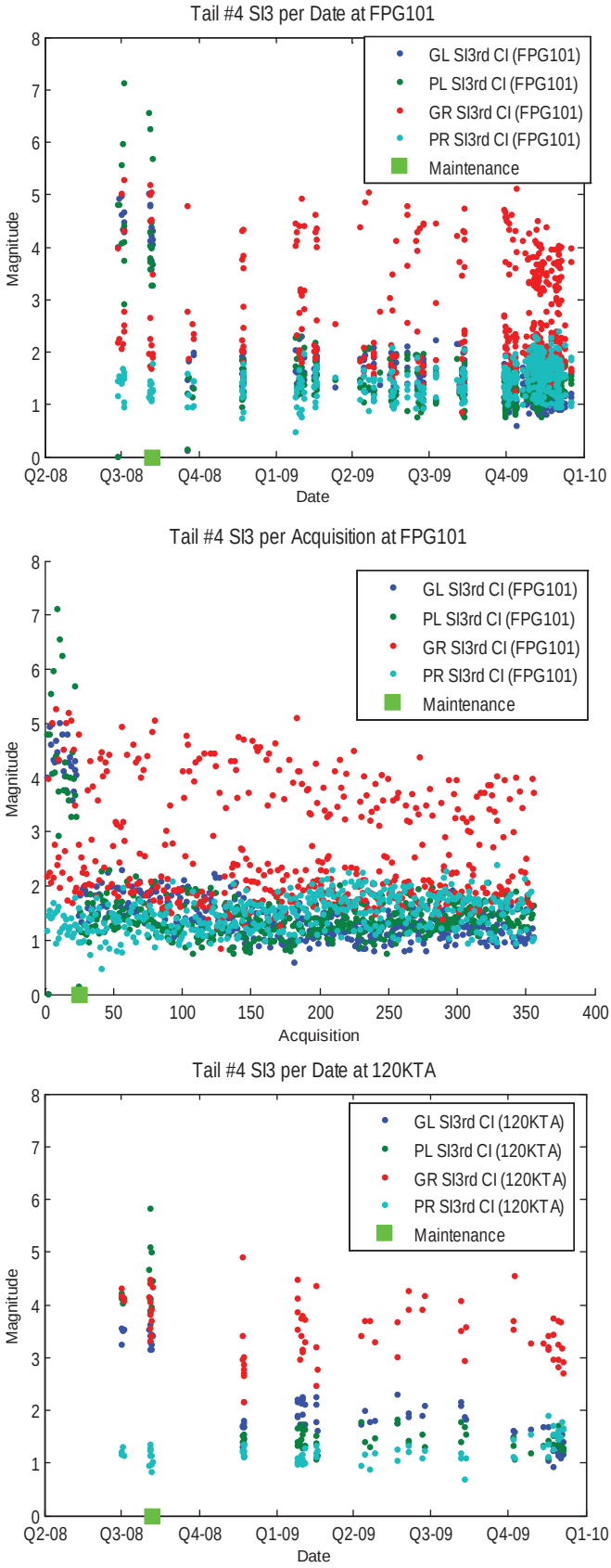

Figure A.4.4.—Tail Number 4 Plots of SI3 per Date, Acquisition and Regime

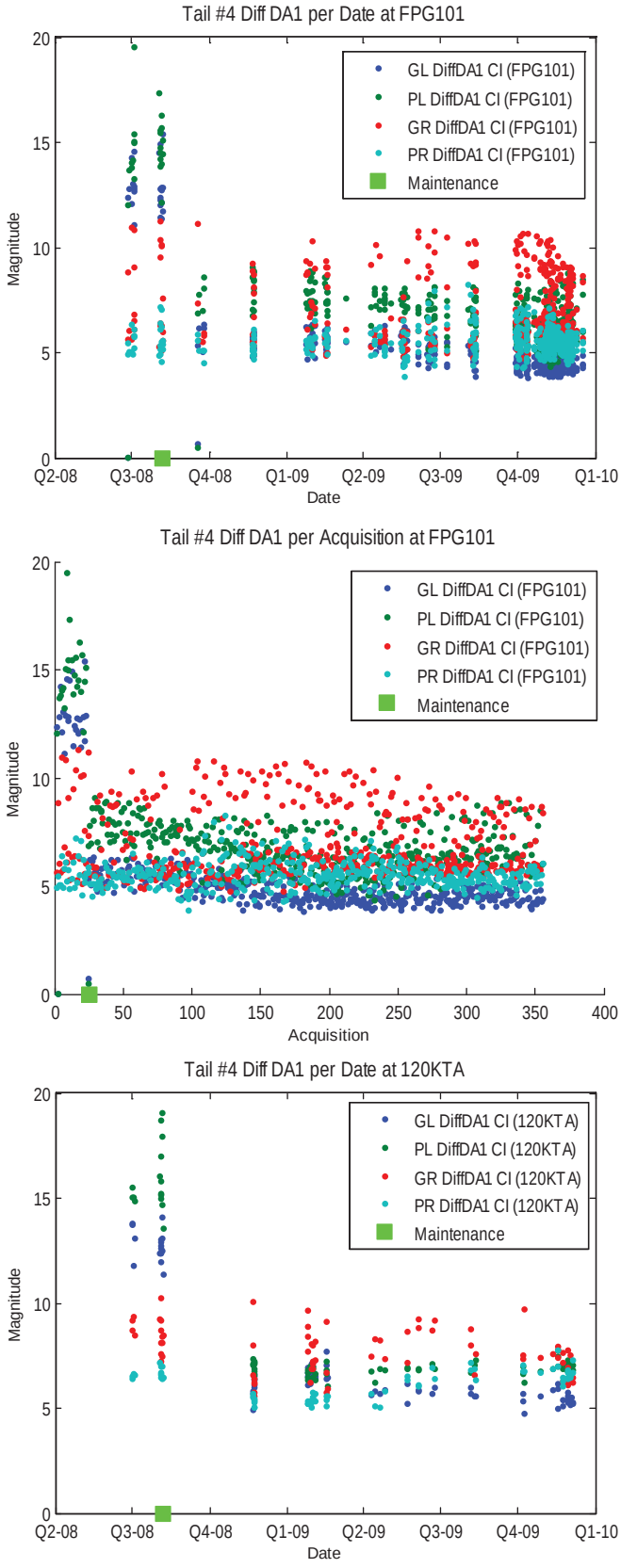

Figure A.4.5.—Tail Number 4 Plots of DiffDA1 per Date, Acquisition and Regime

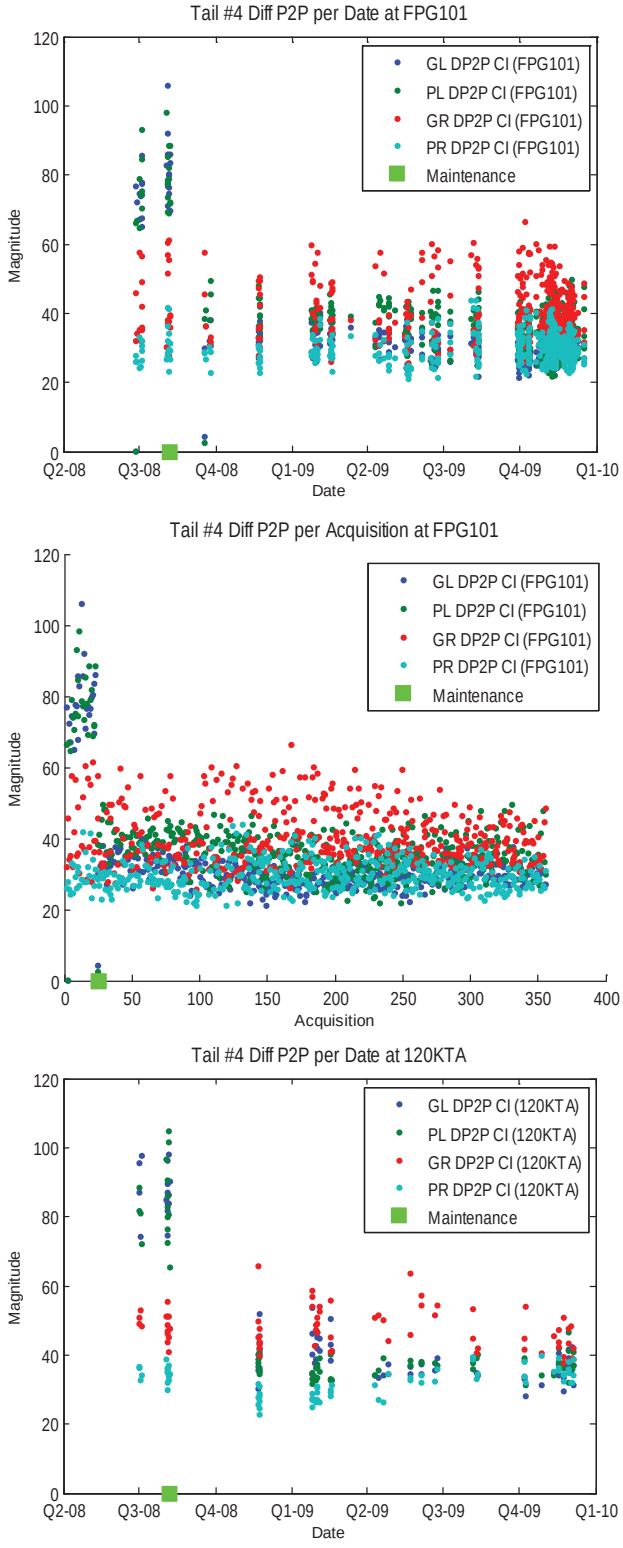

Figure A.4.6.—Tail Number 4 Plots of DP2P per Date, Acquisition and Regime

A.5 Tail Number 5

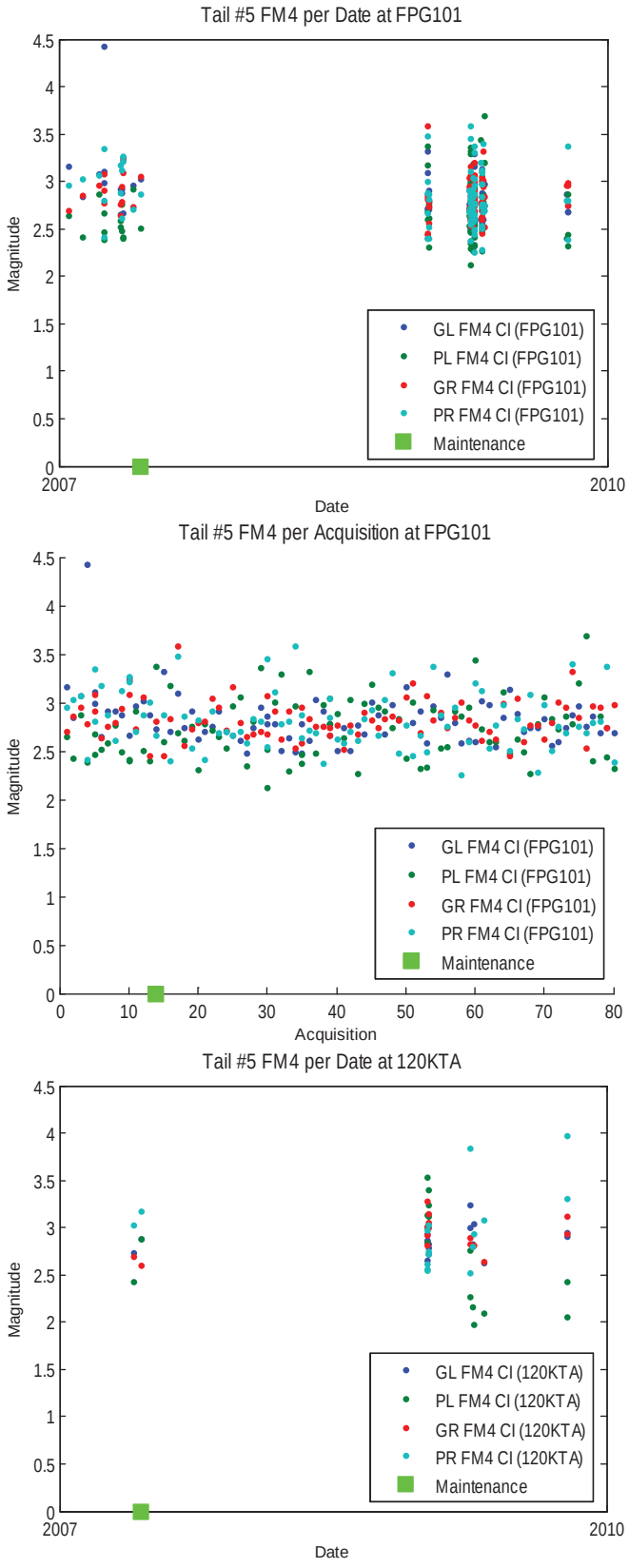

Figure A.5.1.—Tail Number 5 Plots of FM4 per Date, Acquisition and Regime

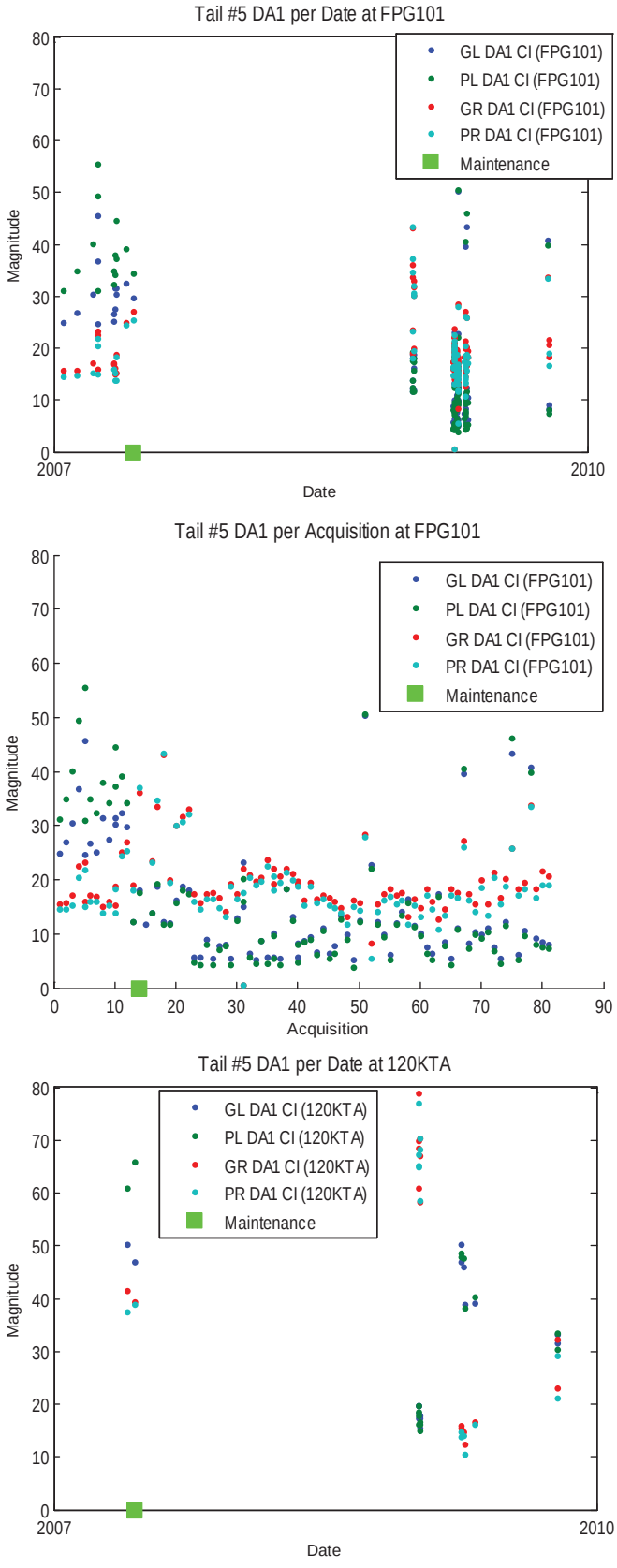

Figure A.5.2.—Tail Number 5 Plots of DA1 per Date, Acquisition and Regime

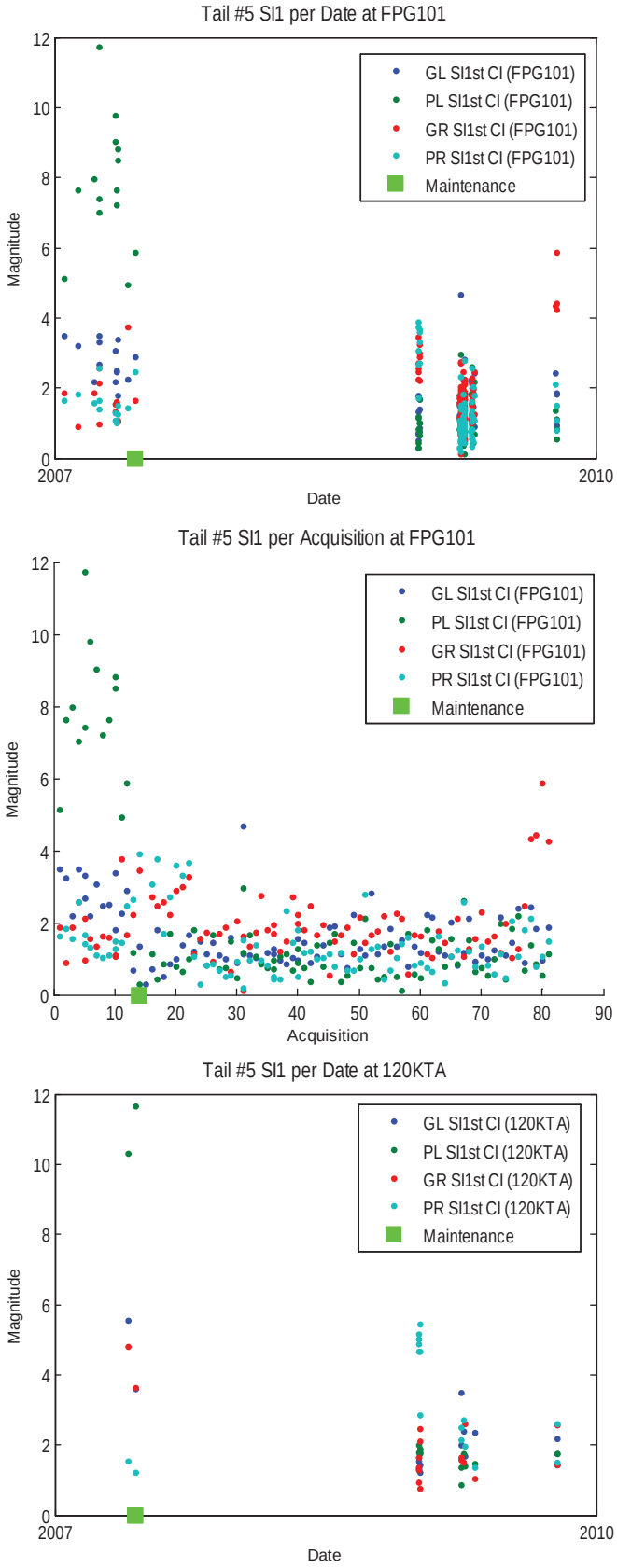

Figure A.5.3.—Tail Number 5 Plots of SI1 per Date, Acquisition and Regime

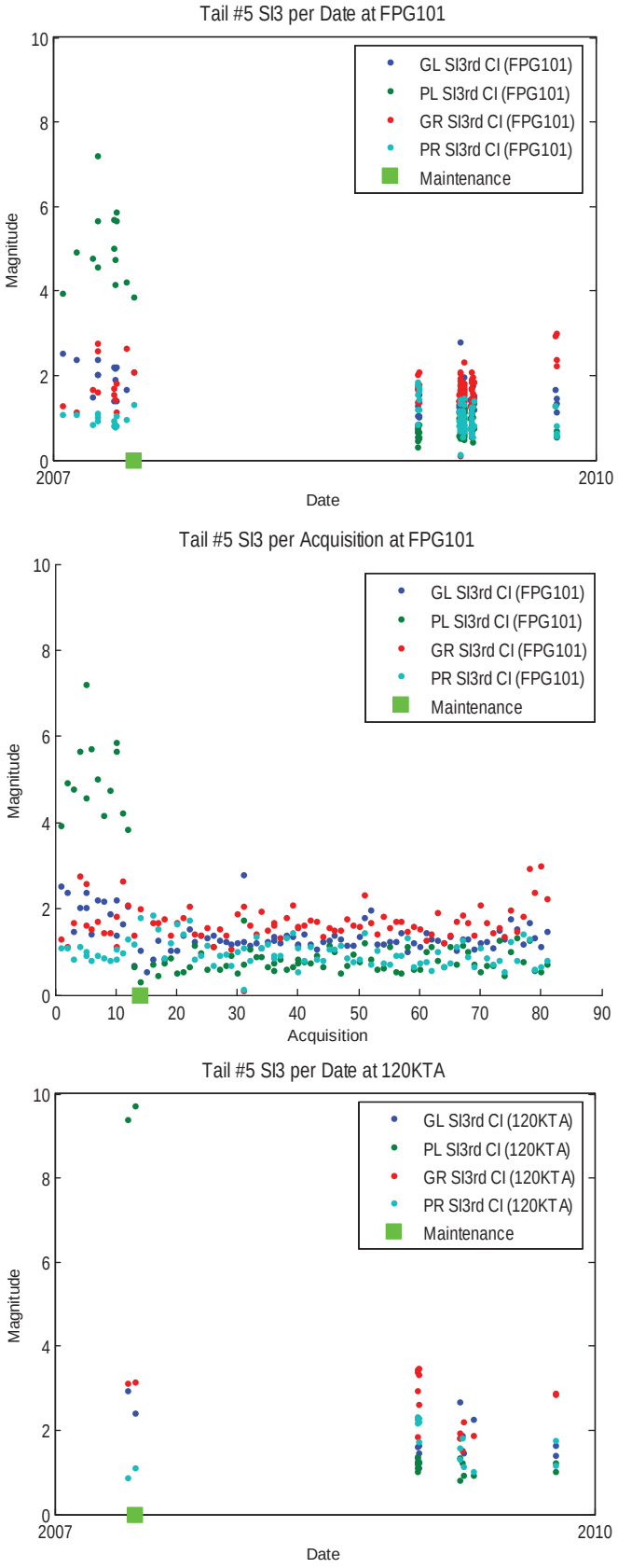

Figure A.5.4.—Tail Number 5 Plots of SI3 per Date, Acquisition and Regime

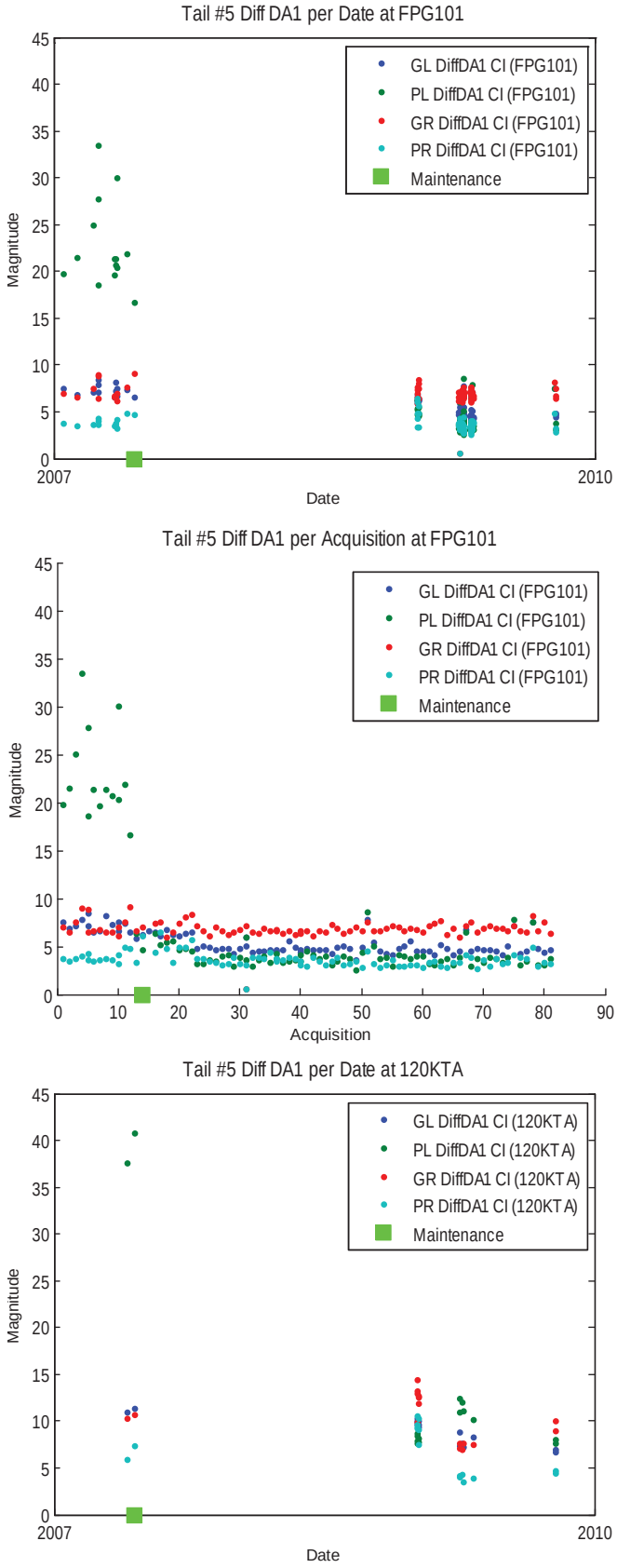

Figure A.5.5.—Tail Number 5 Plots of DiffDA1 per Date, Acquisition and Regime

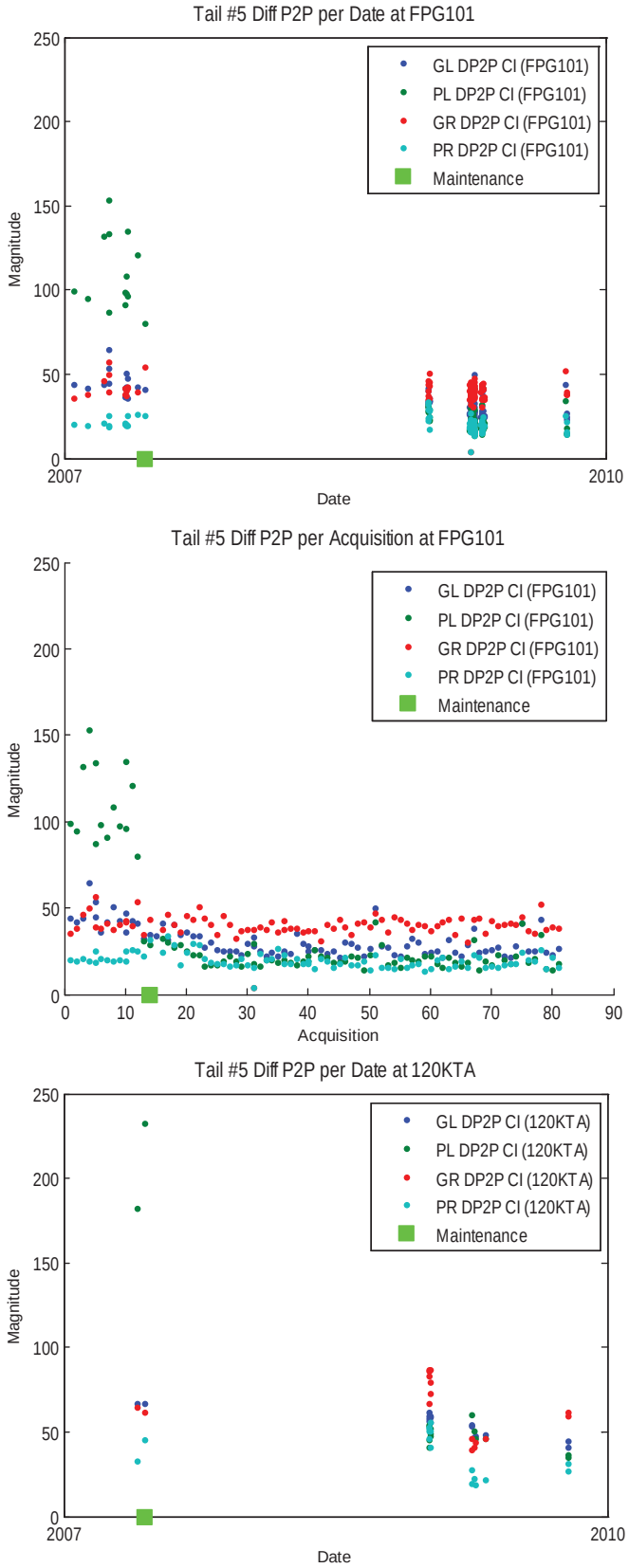

Figure A.5.6.—Tail Number 5 Plots of DP2P per Date, Acquisition and Regime

A.6 Tail Number 6

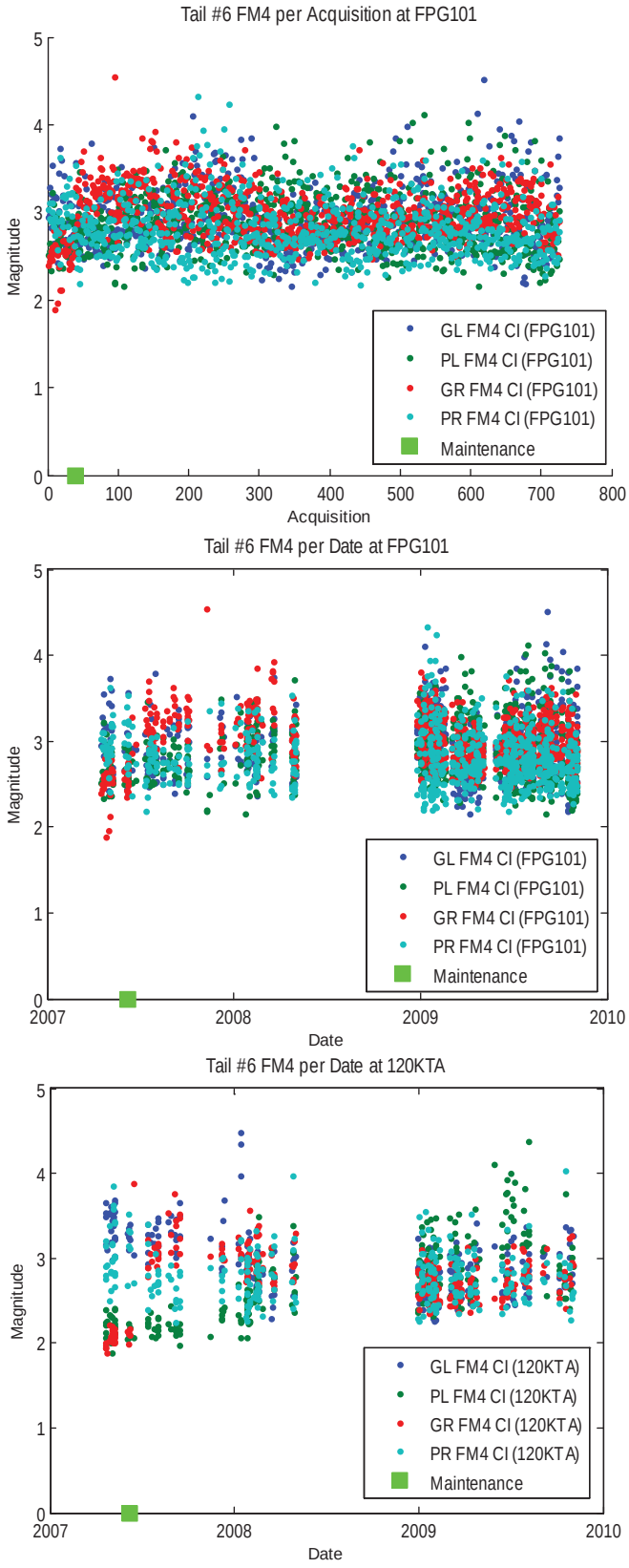

Figure A.6.1.—Tail Number 6 Plots of FM4 per Date, Acquisition and Regime

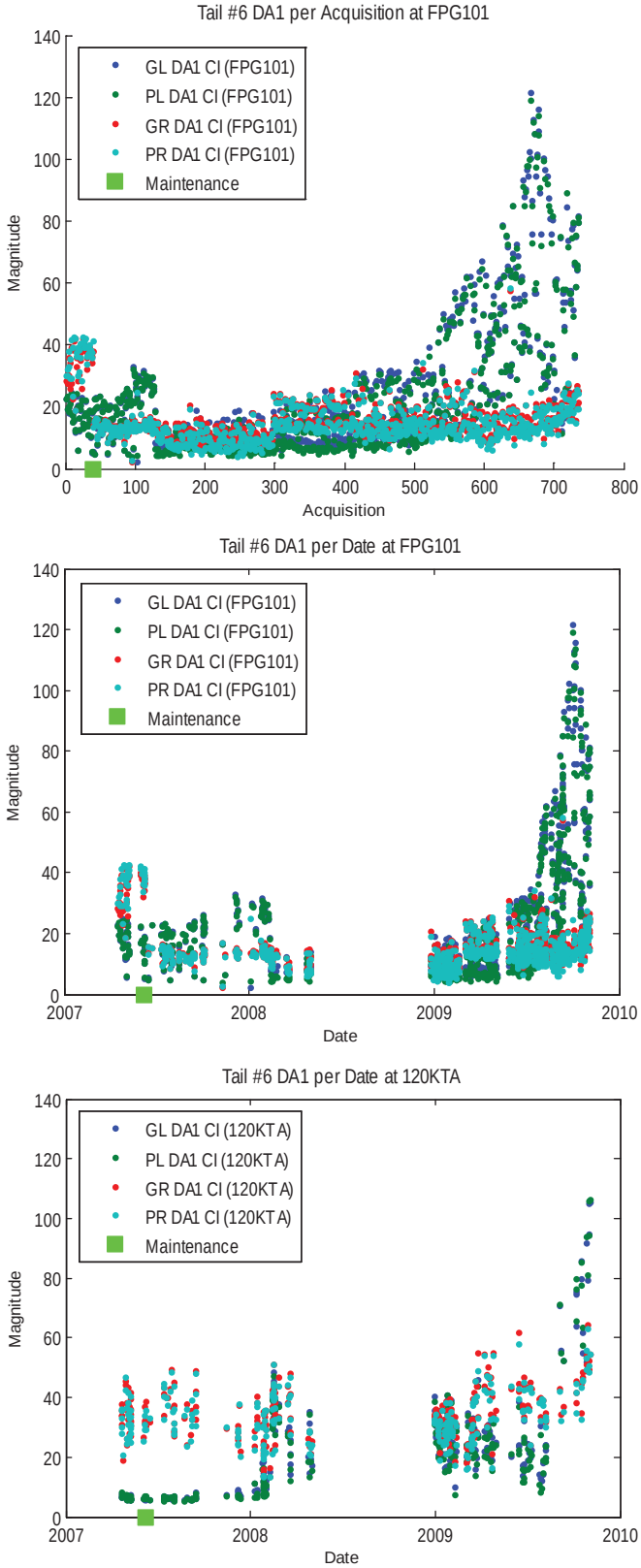

Figure A.6.2.—Tail Number 6 Plots of DA1 per Date, Acquisition and Regime

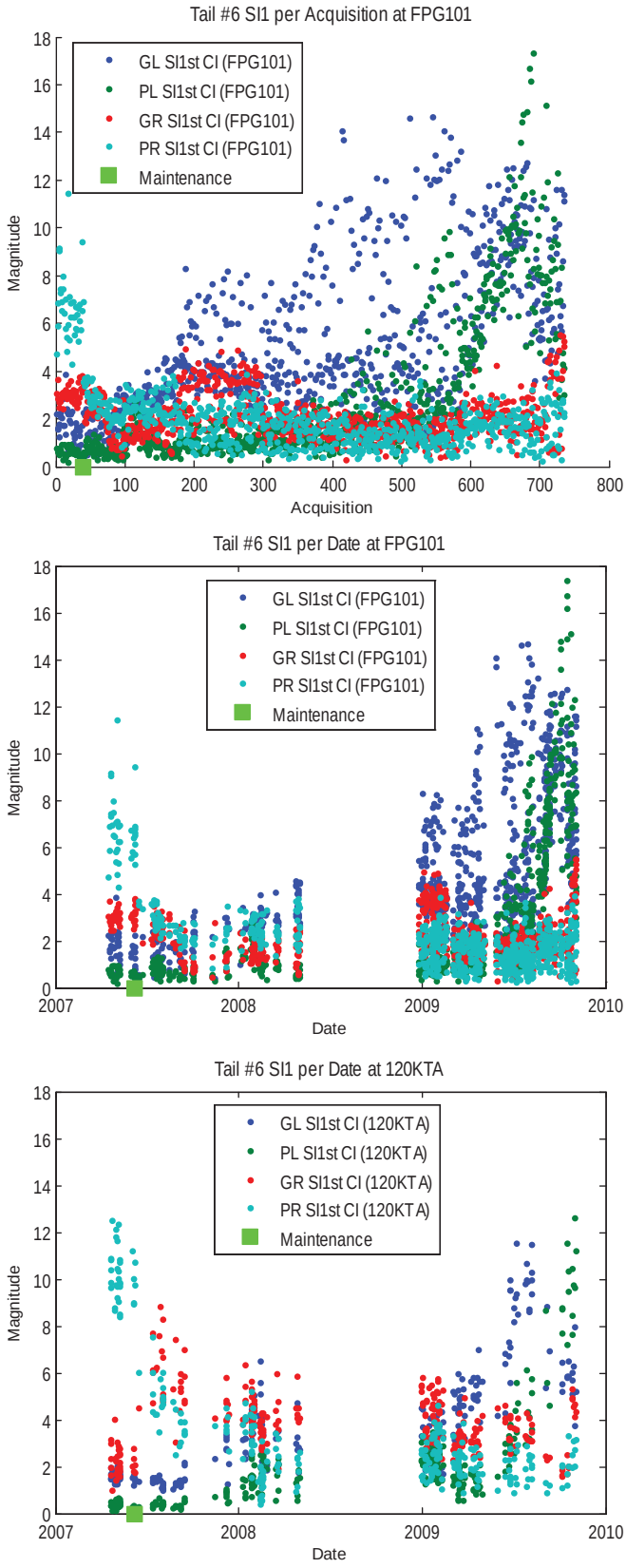

Figure A.6.3.—Tail Number 6 Plots of SI1 per Date, Acquisition and Regime

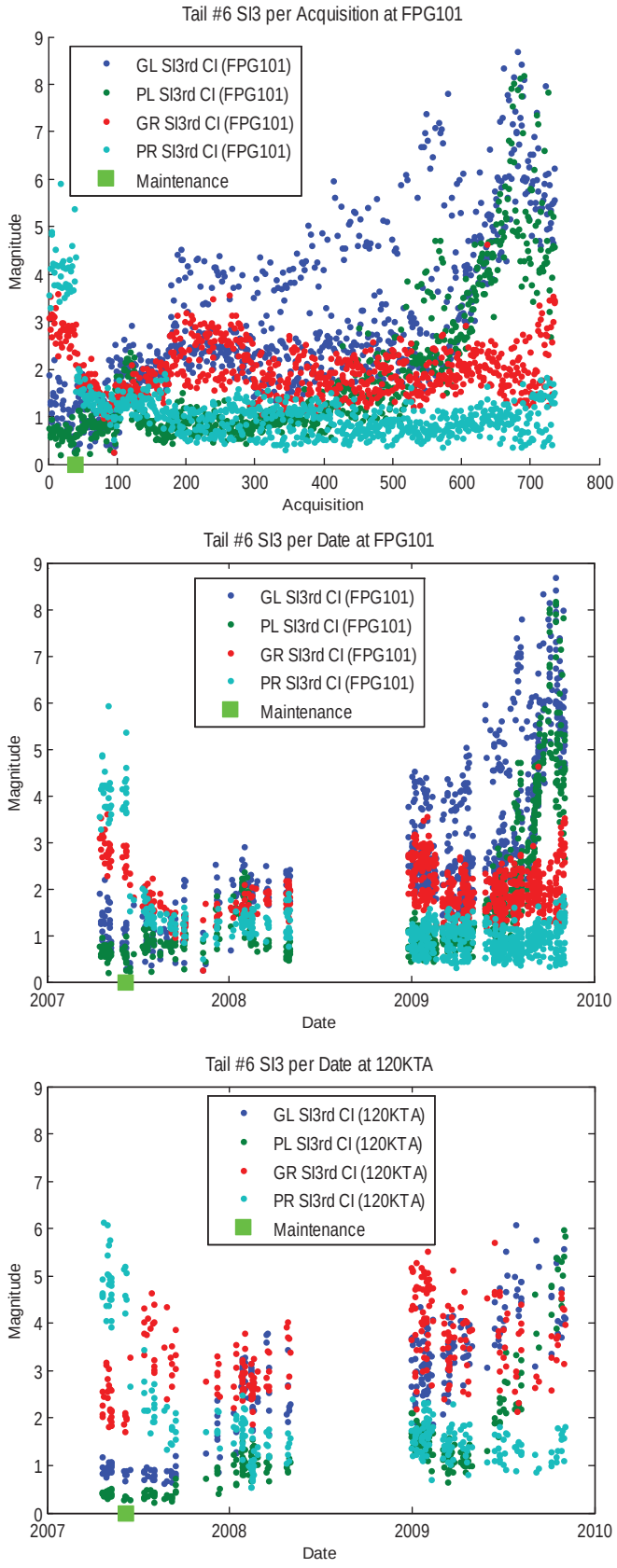

Figure A.6.4.—Tail Number 6 Plots of SI3 per Date, Acquisition and Regime

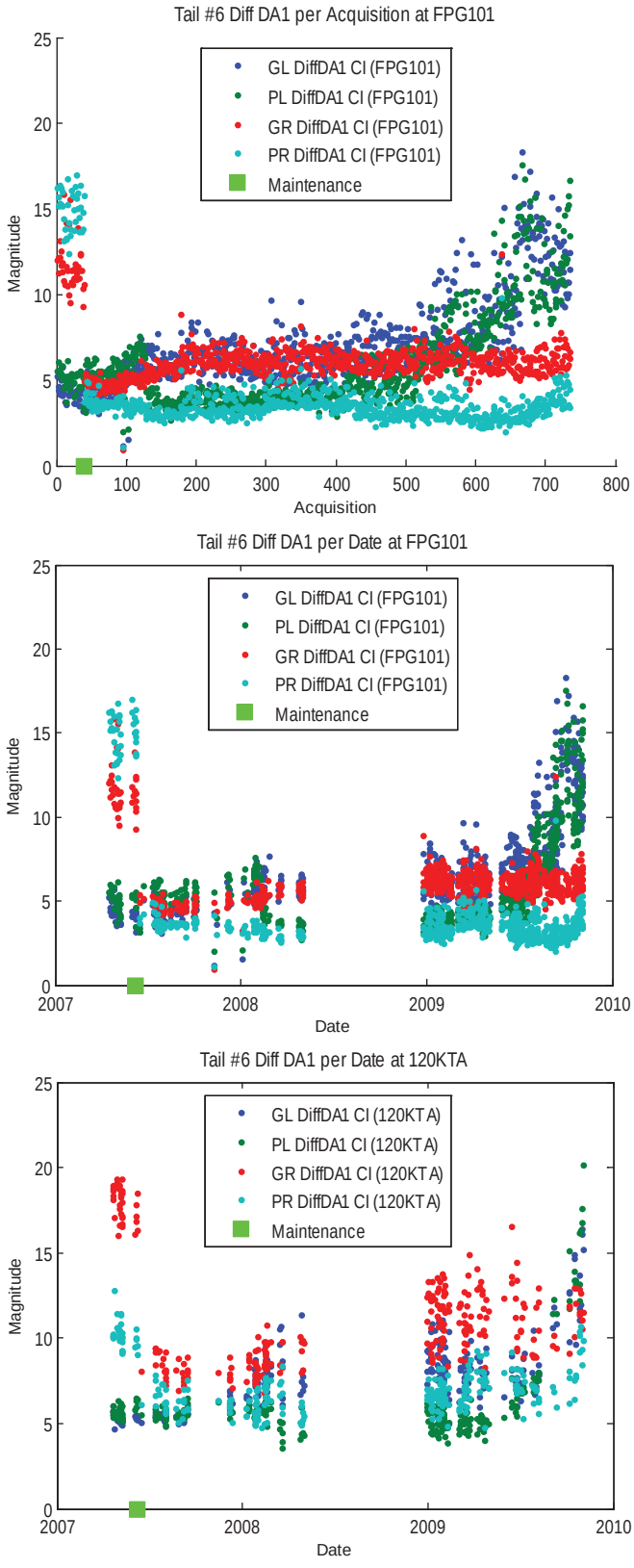

Figure A.6.5.—Tail Number 6 Plots of DiffDA1 per Date, Acquisition and Regime

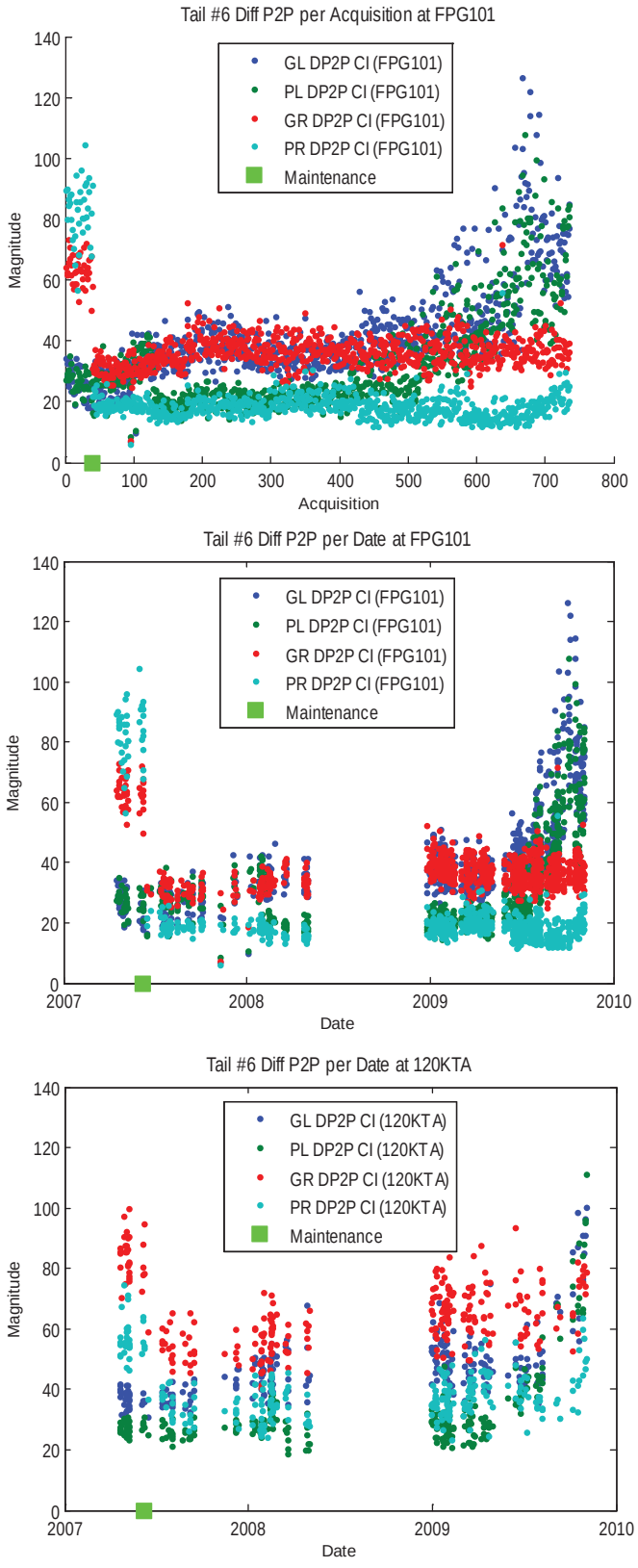

Figure A.6.6.—Tail Number 6 Plots of D2P2 per Date, Acquisition and Regime

A.7 Tail Number 7

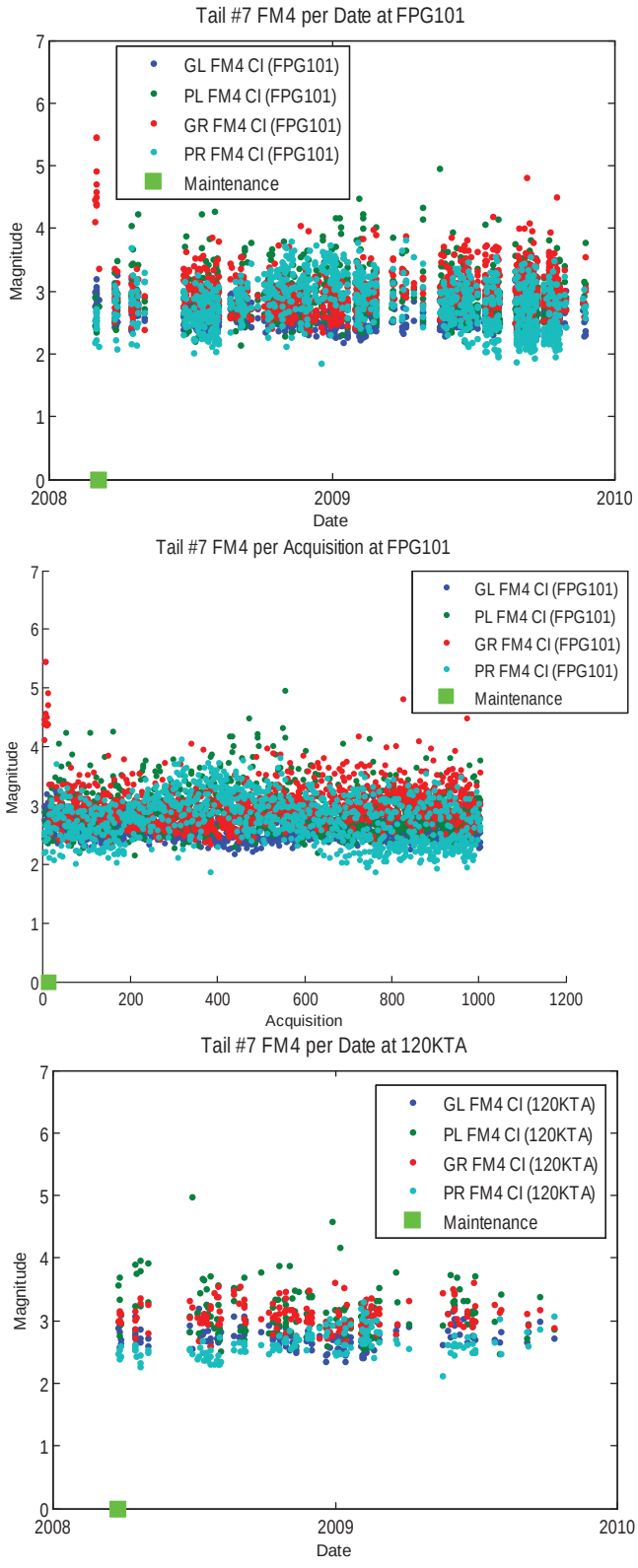

Figure A.7.1.—Tail Number 7 Plots of FM4 per Date, Acquisition and Regime

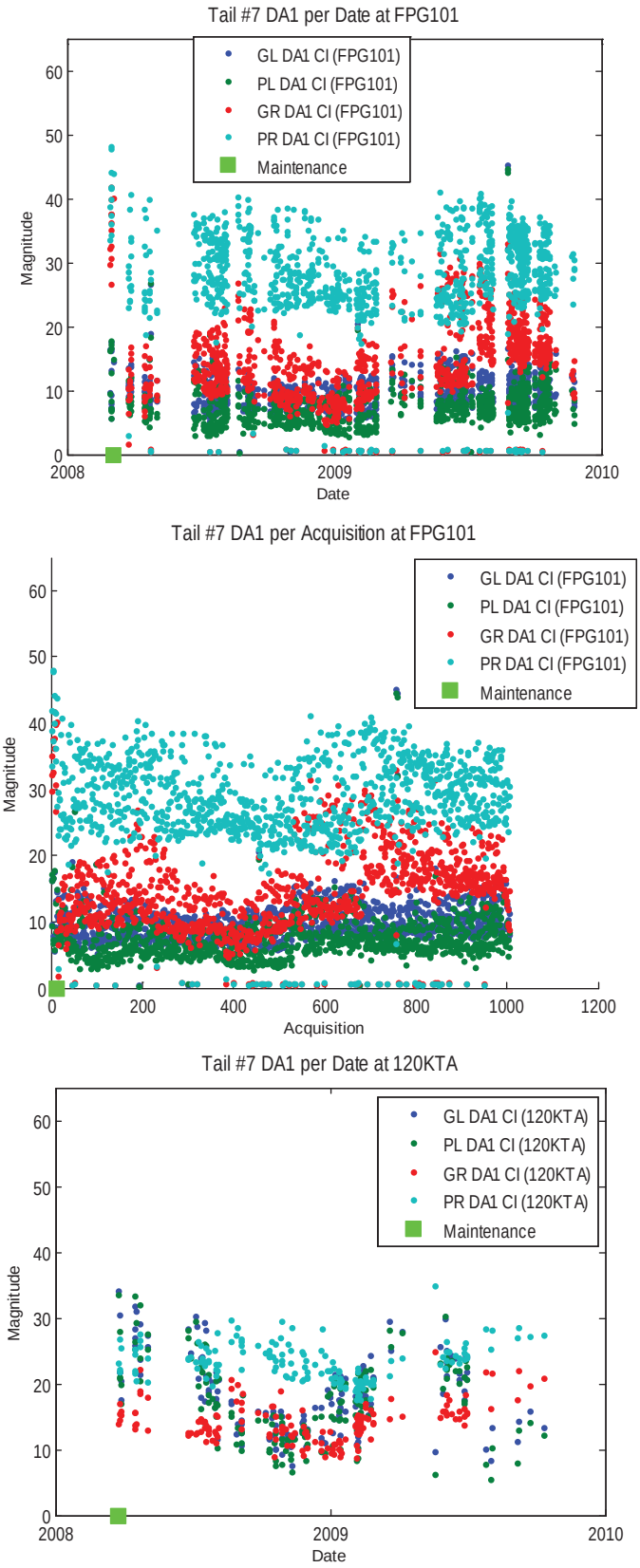

Figure A.7.2.—Tail Number 7 Plots of DA1 per Date, Acquisition and Regime

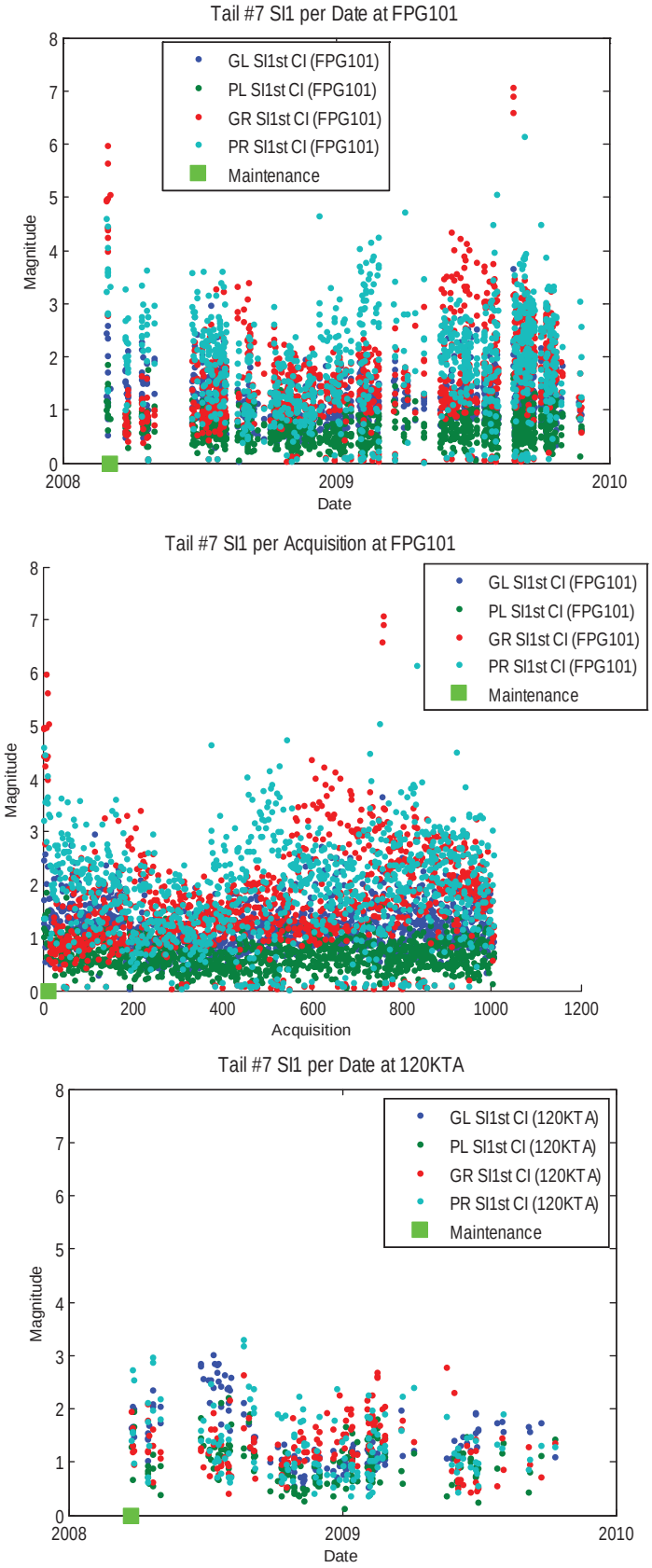

Figure A.7.3.—Tail Number 7 Plots of SI1 per Date, Acquisition and Regime

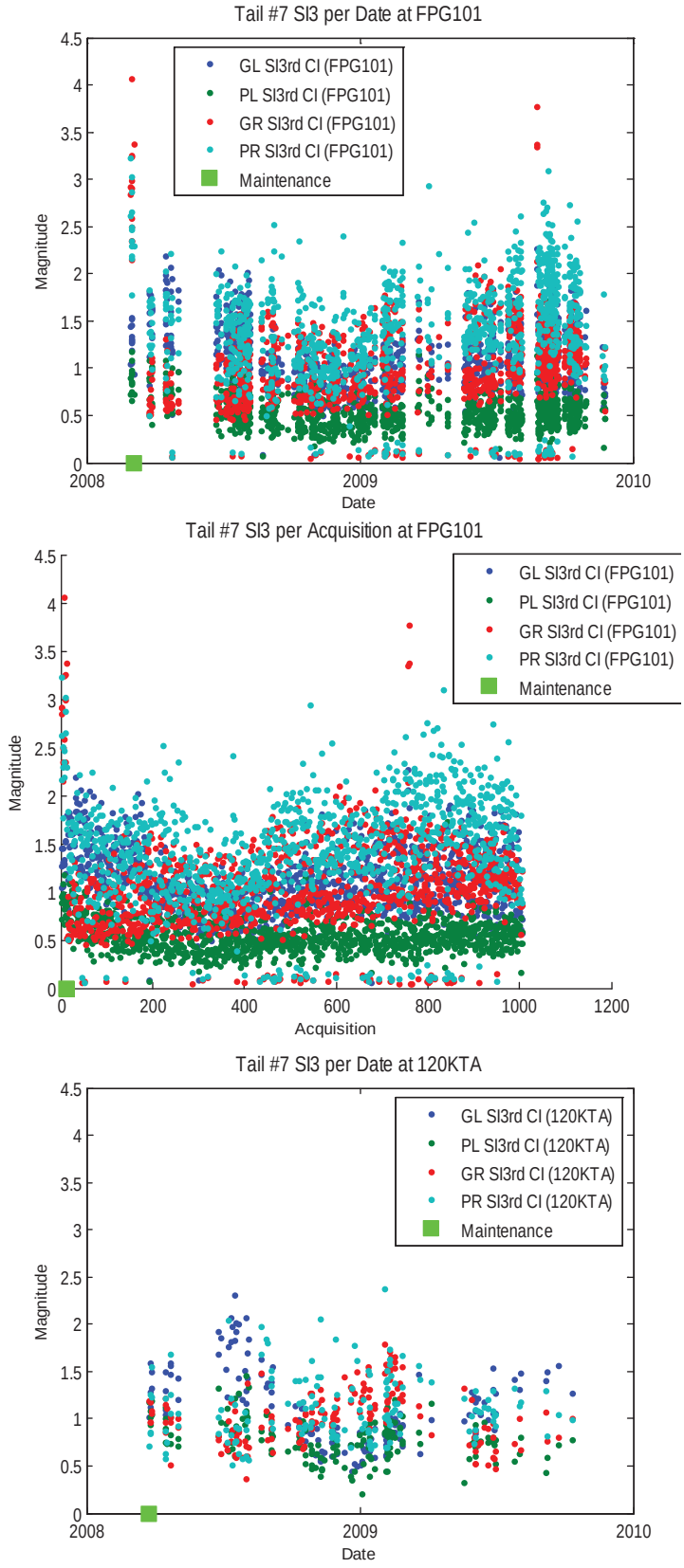

Figure A.7.4.—Tail Number 7 Plots of SI3 per Date, Acquisition and Regime

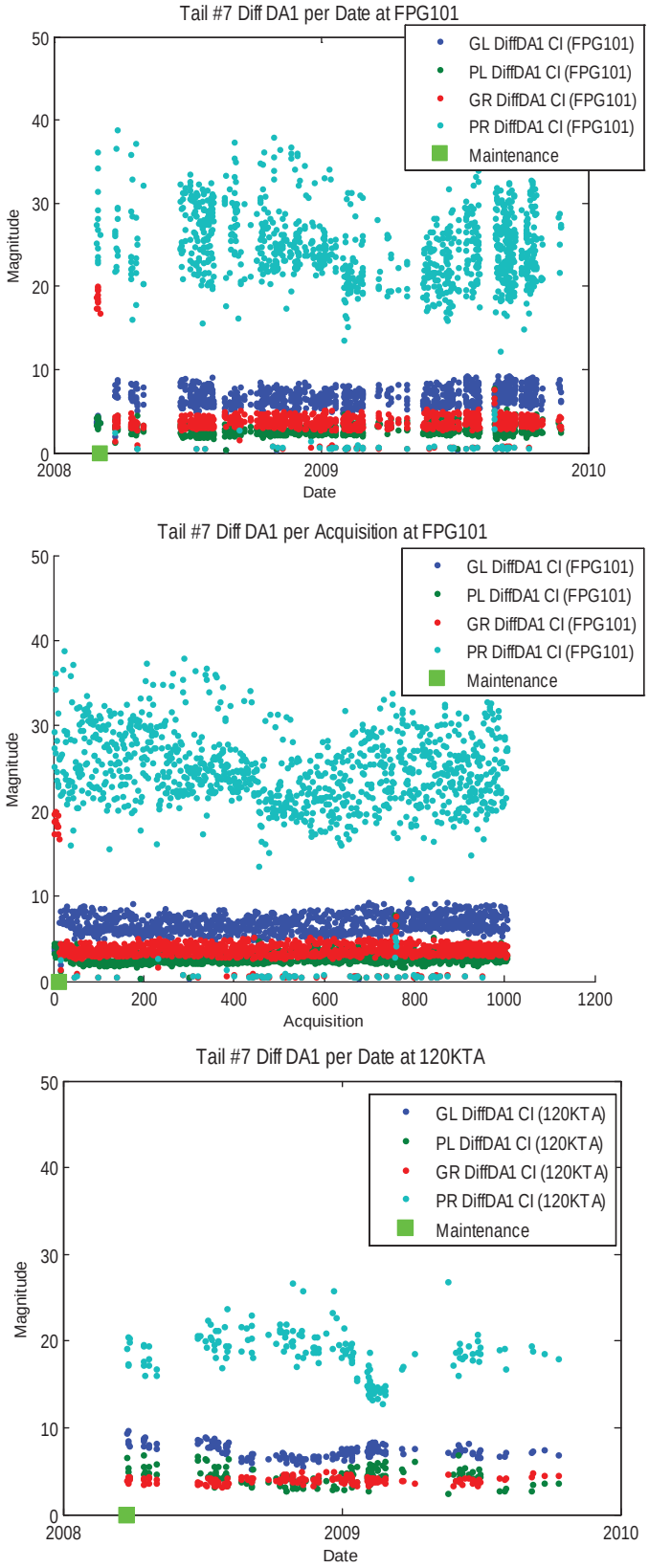

Figure A.7.5.—Tail Number 7 Plots of DiffDA1 per Date, Acquisition and Regime

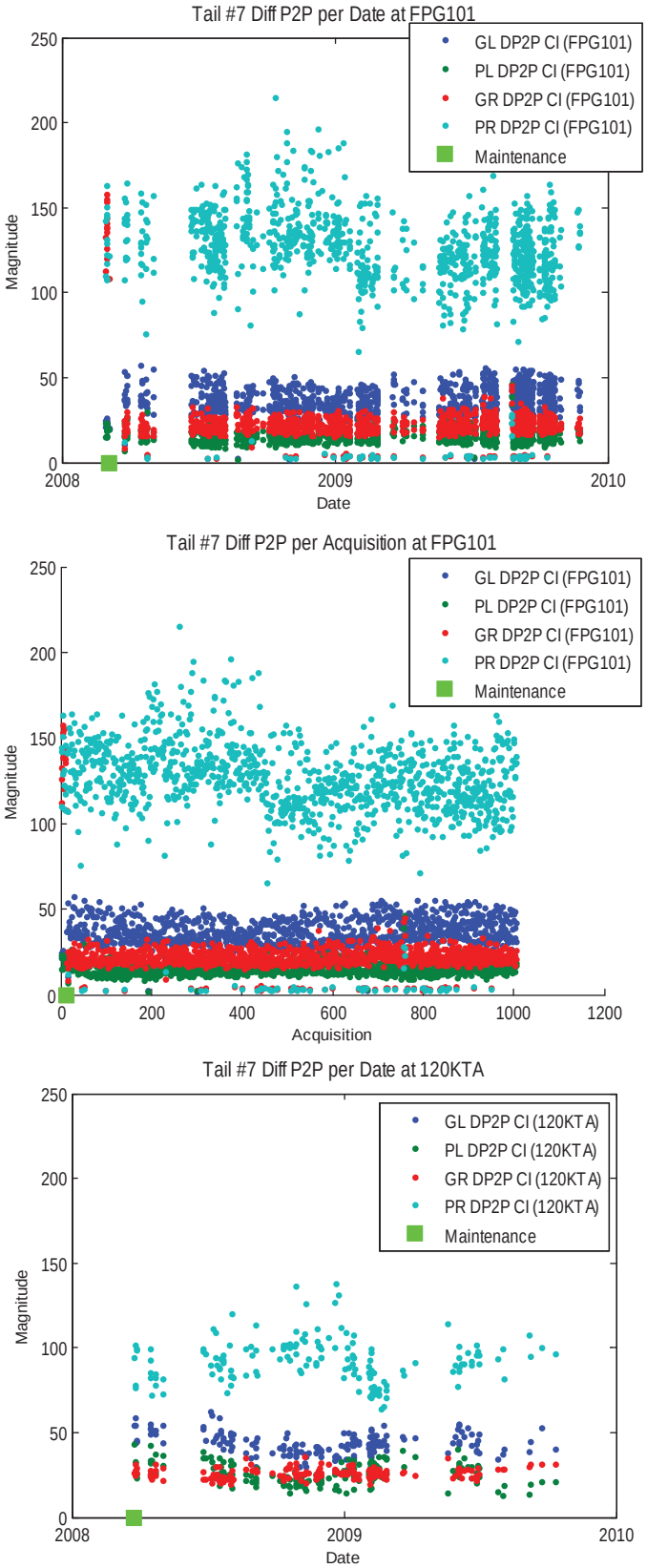

Figure A.7.6.—Tail Number 7 Plots of D2P2 per Date, Acquisition and Regime

A.8 Tail Number 8

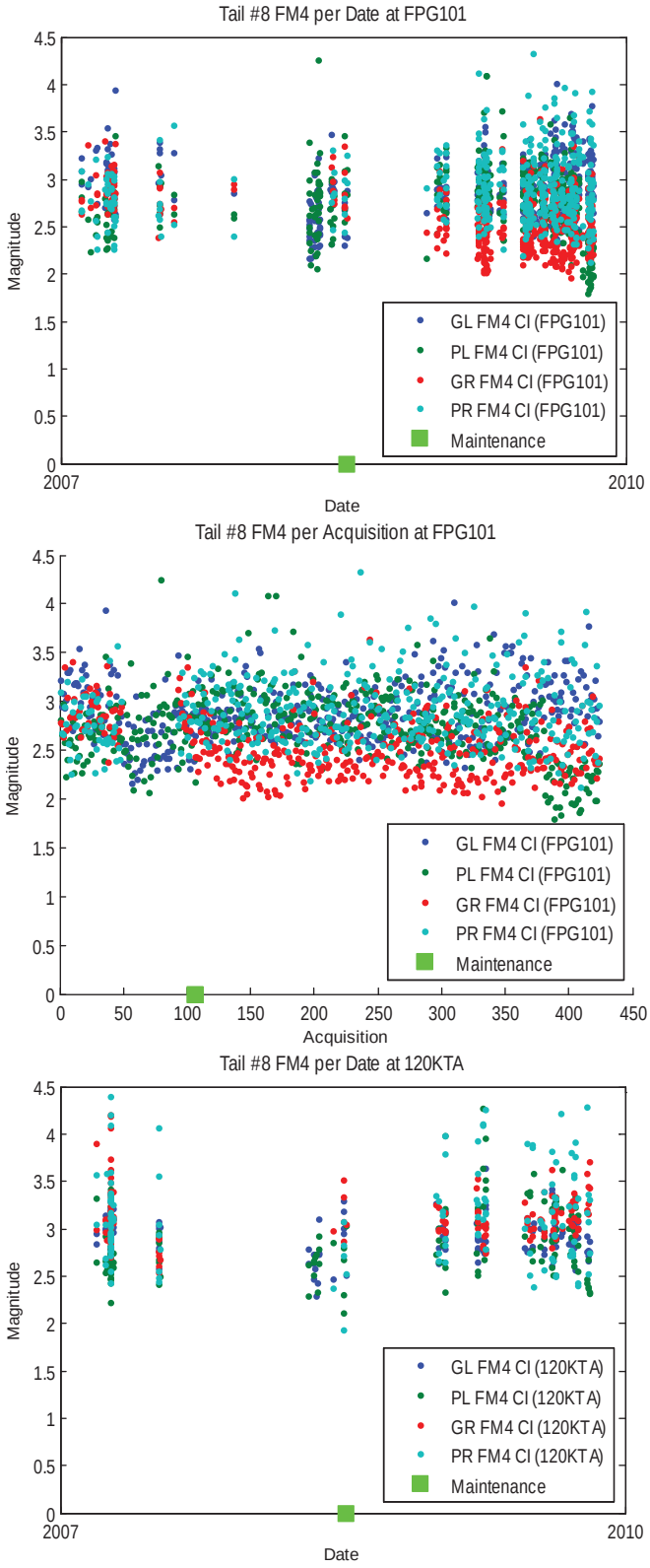

Figure A.8.1.—Tail Number 8 Plots of FM4 per Date, Acquisition and Regime

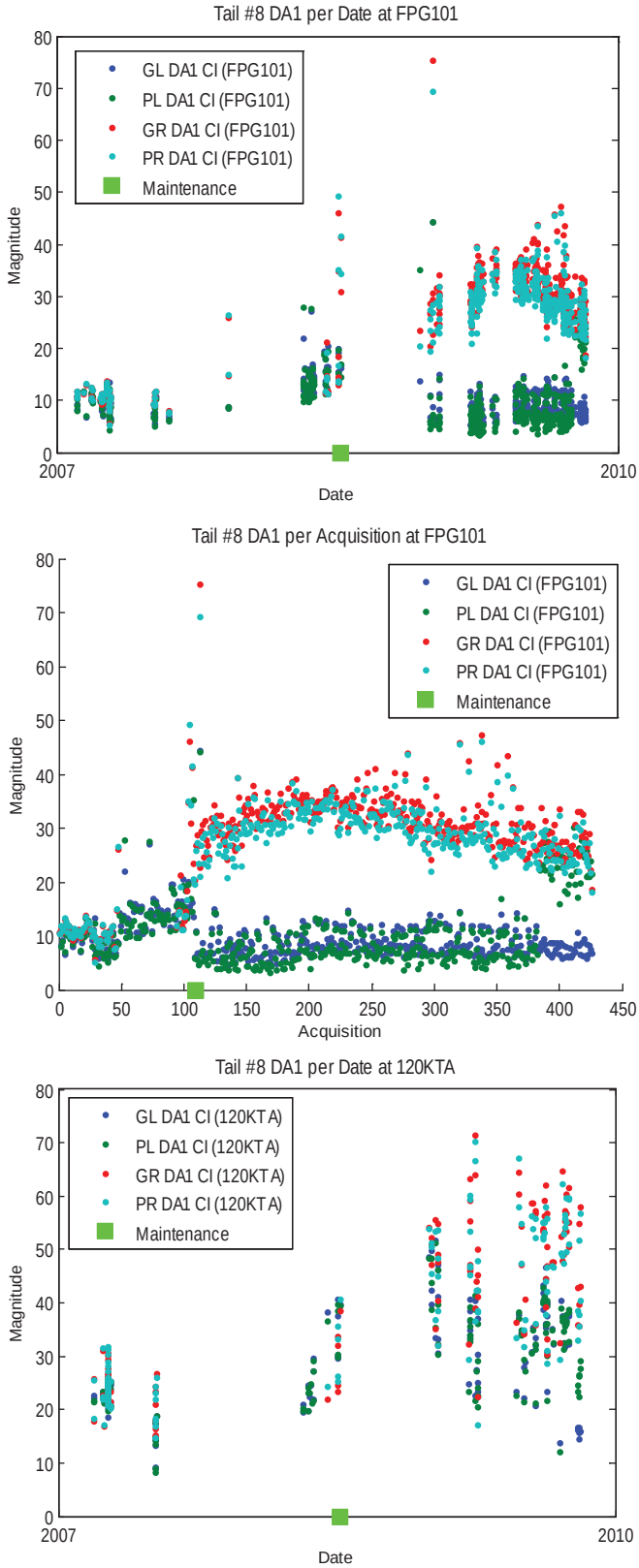

Figure A.8.2.—Tail Number 8 Plots of DA1 per Date, Acquisition and Regime

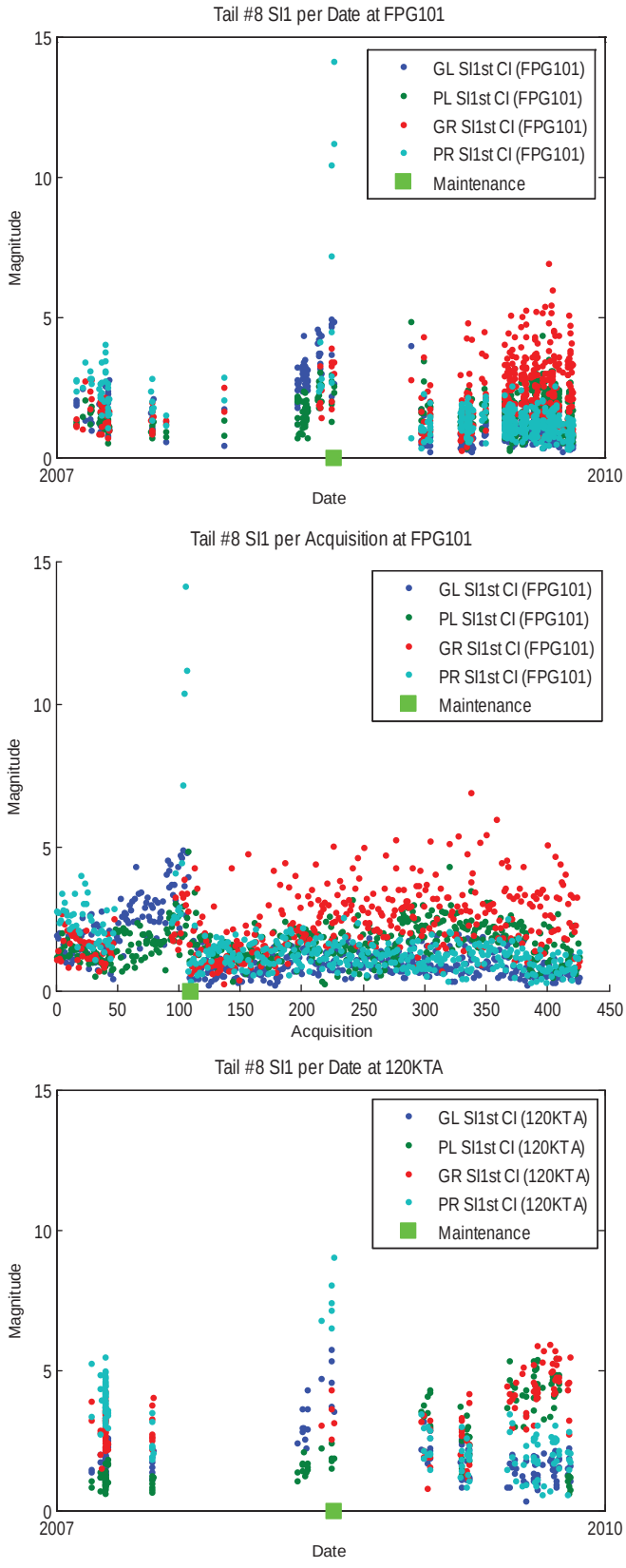

Figure A.8.3.—Tail Number 8 Plots of SI1 per Date, Acquisition and Regime

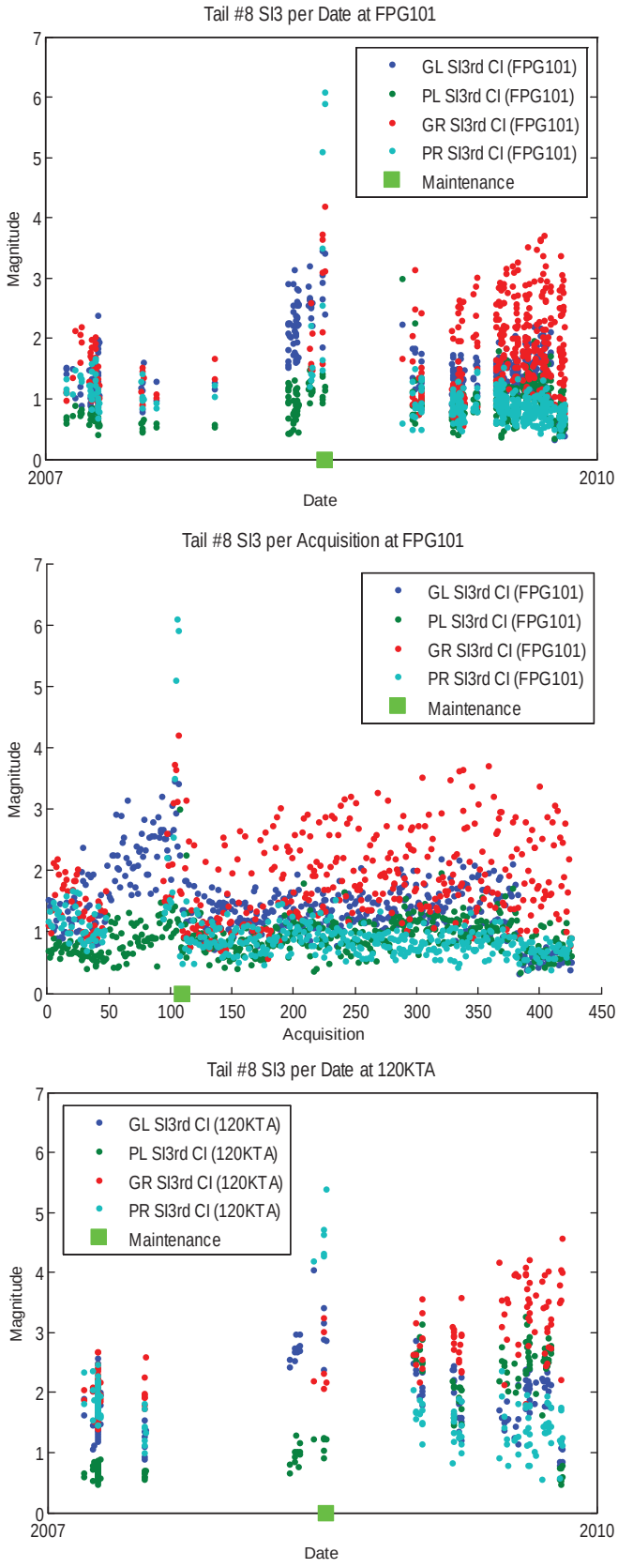

Figure A.8.4.—Tail Number 8 Plots of SI3 per Date, Acquisition and Regime

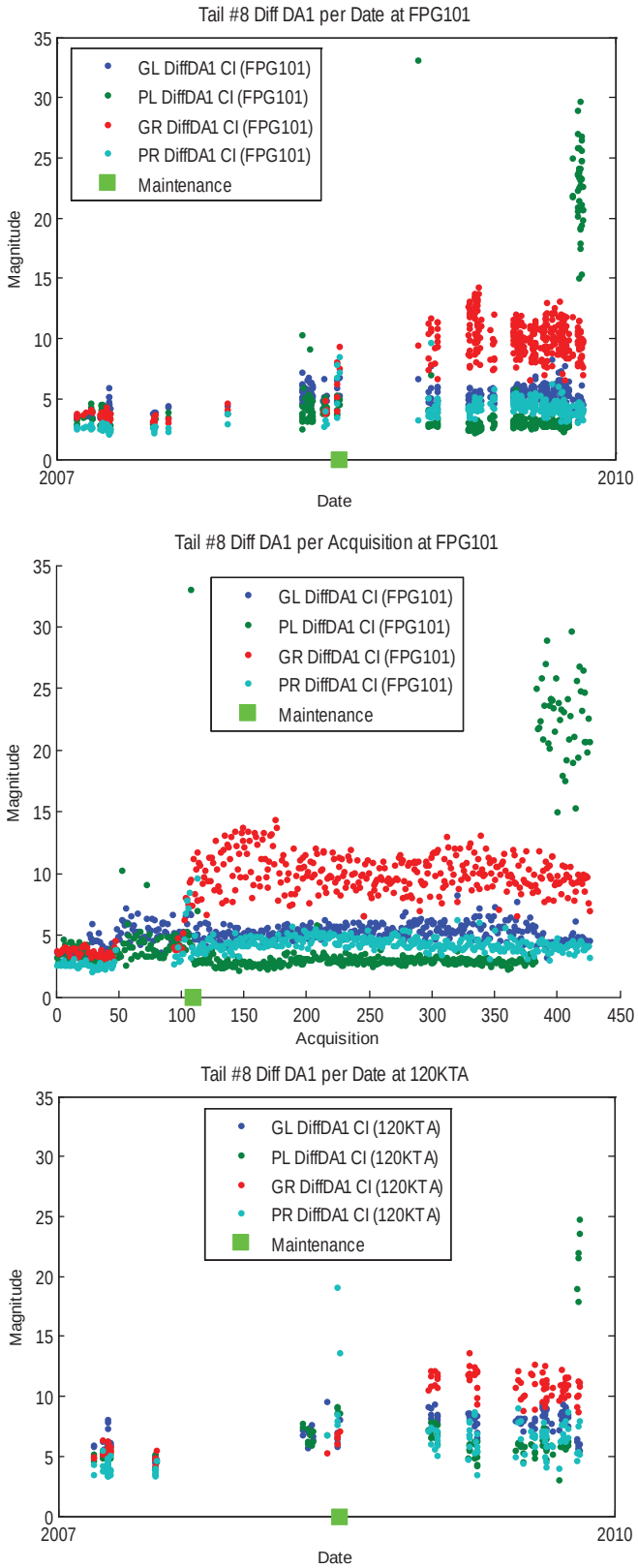

Figure A.8.5.—Tail Number 8 Plots of DiffDA1 per Date, Acquisition and Regime

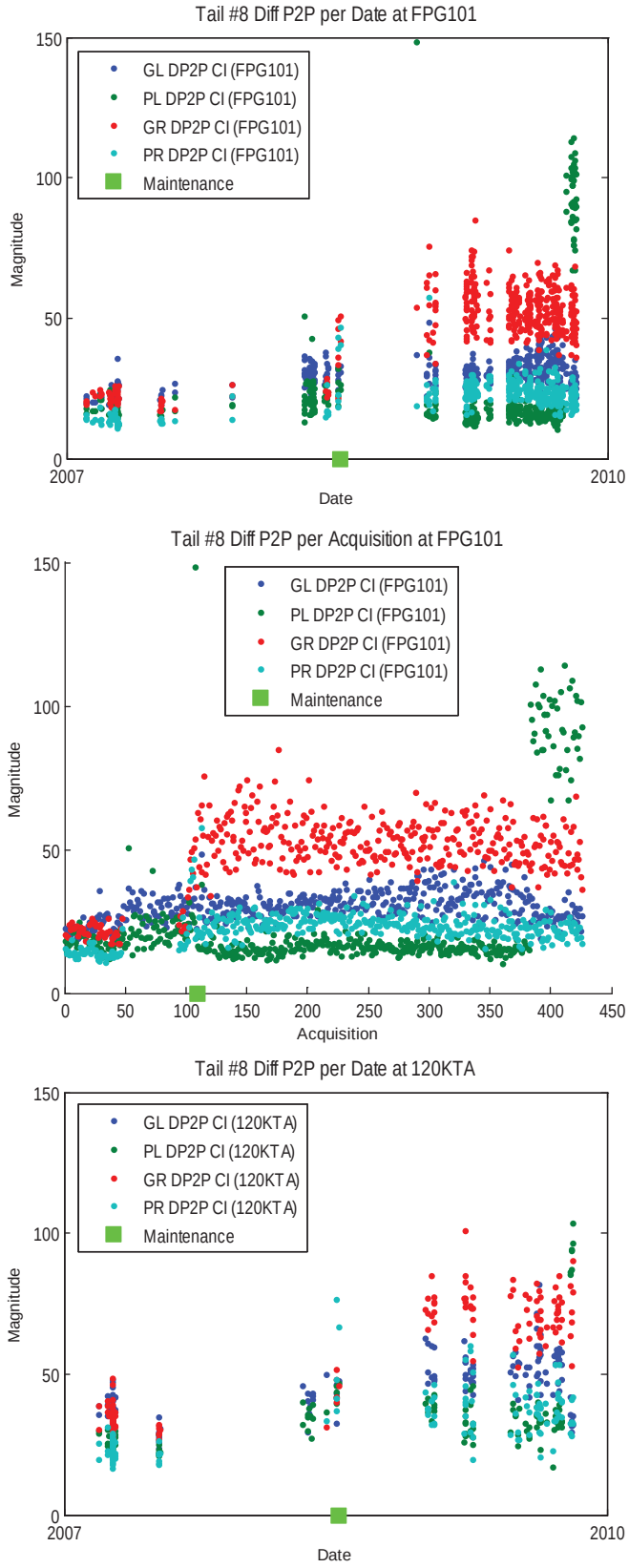

Figure A.8.6.—Tail Number 8 Plots of DP2P per Date, Acquisition and Regime

A.9 Tail Number 9

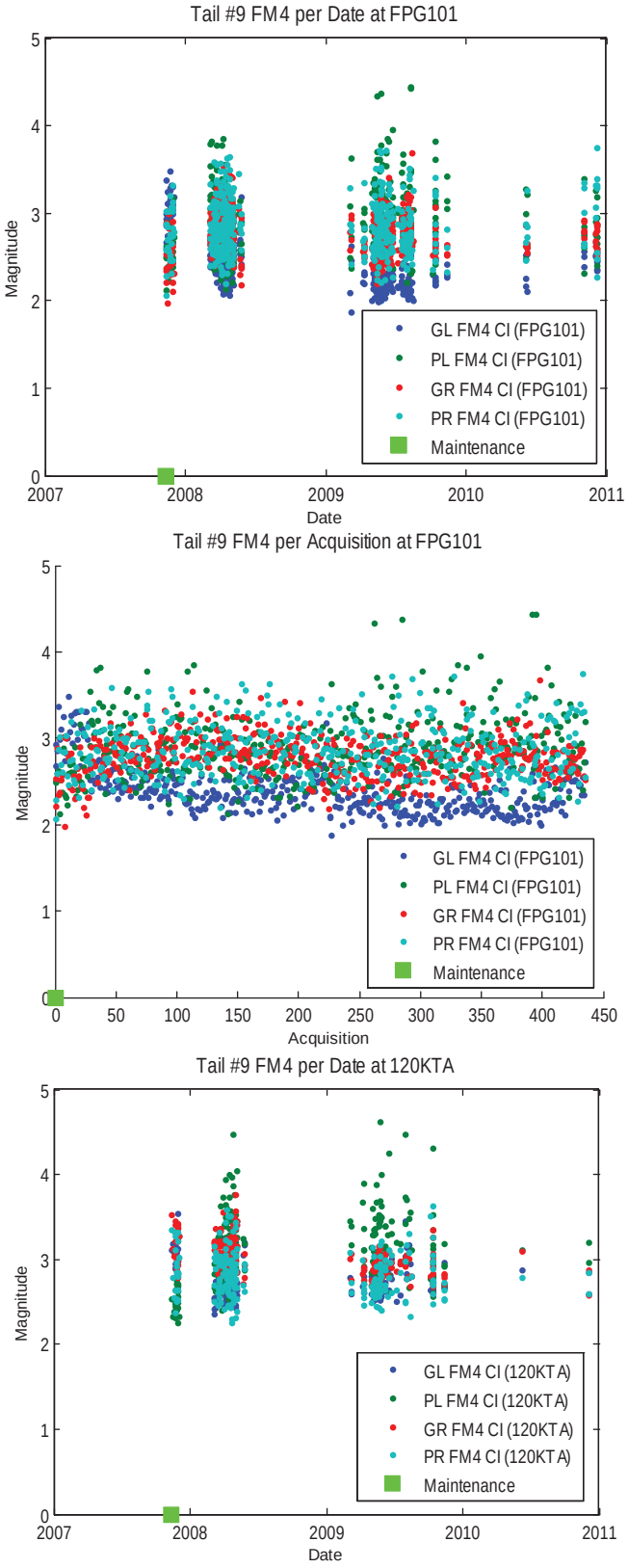

Figure A.9.1.—Tail Number 9 Plots of FM4 per Date, Acquisition and Regime

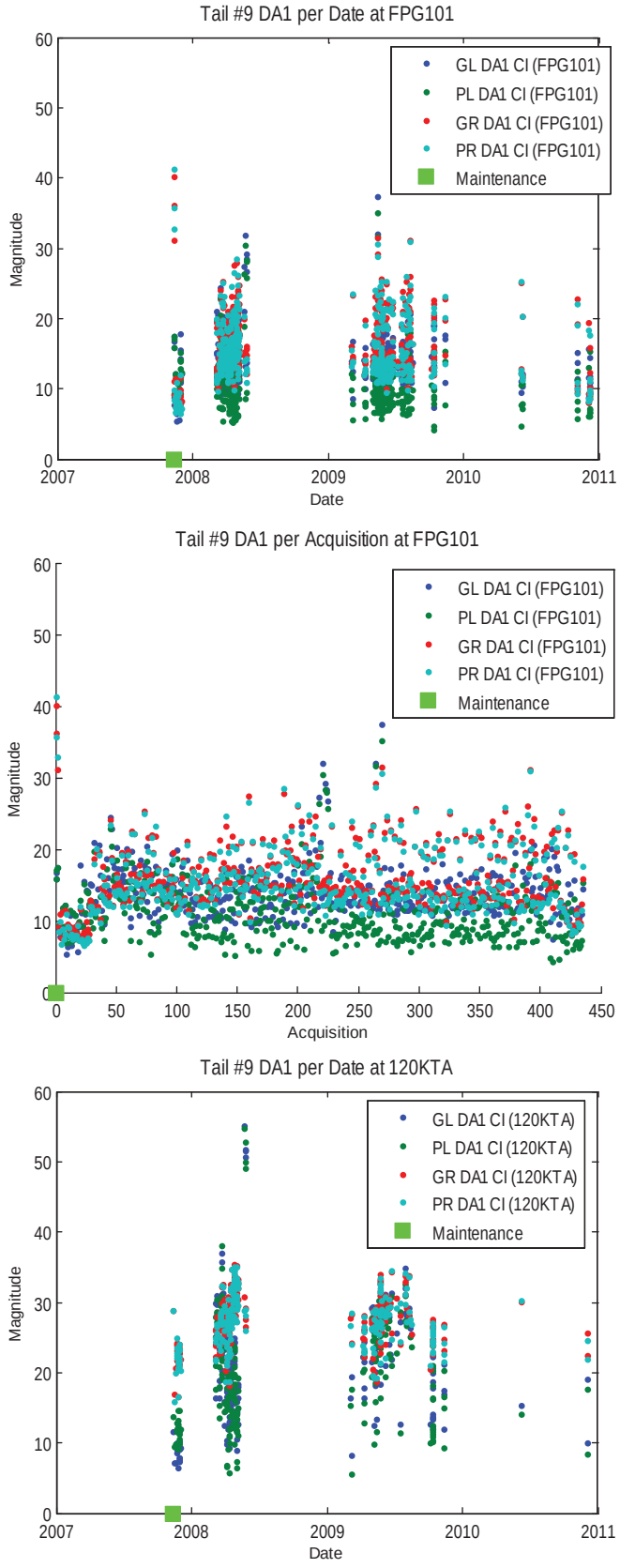

Figure A.9.2.—Tail Number 9 Plots of DA1 per Date, Acquisition and Regime

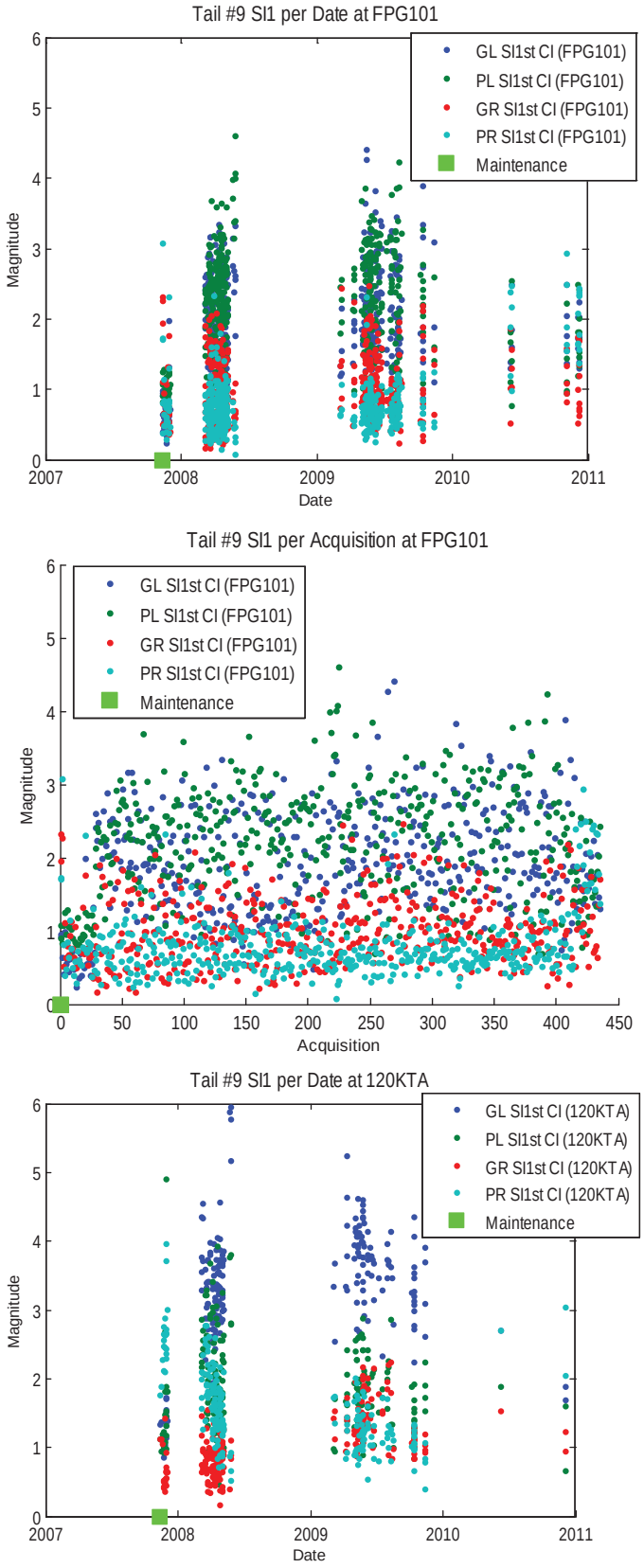

Figure A.9.3.—Tail Number 9 Plots of SI1 per Date, Acquisition and Regime

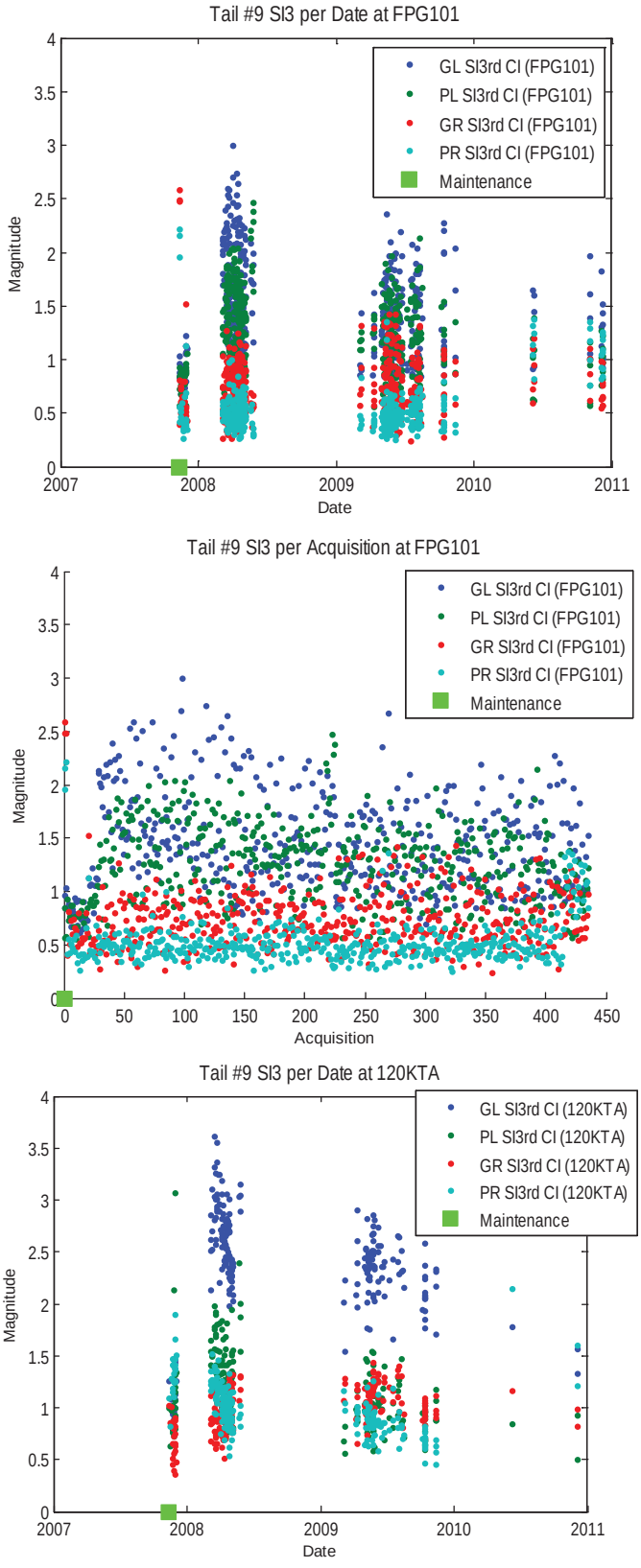

Figure A.9.4.—Tail Number 9 Plots of SI3 per Date, Acquisition and Regime

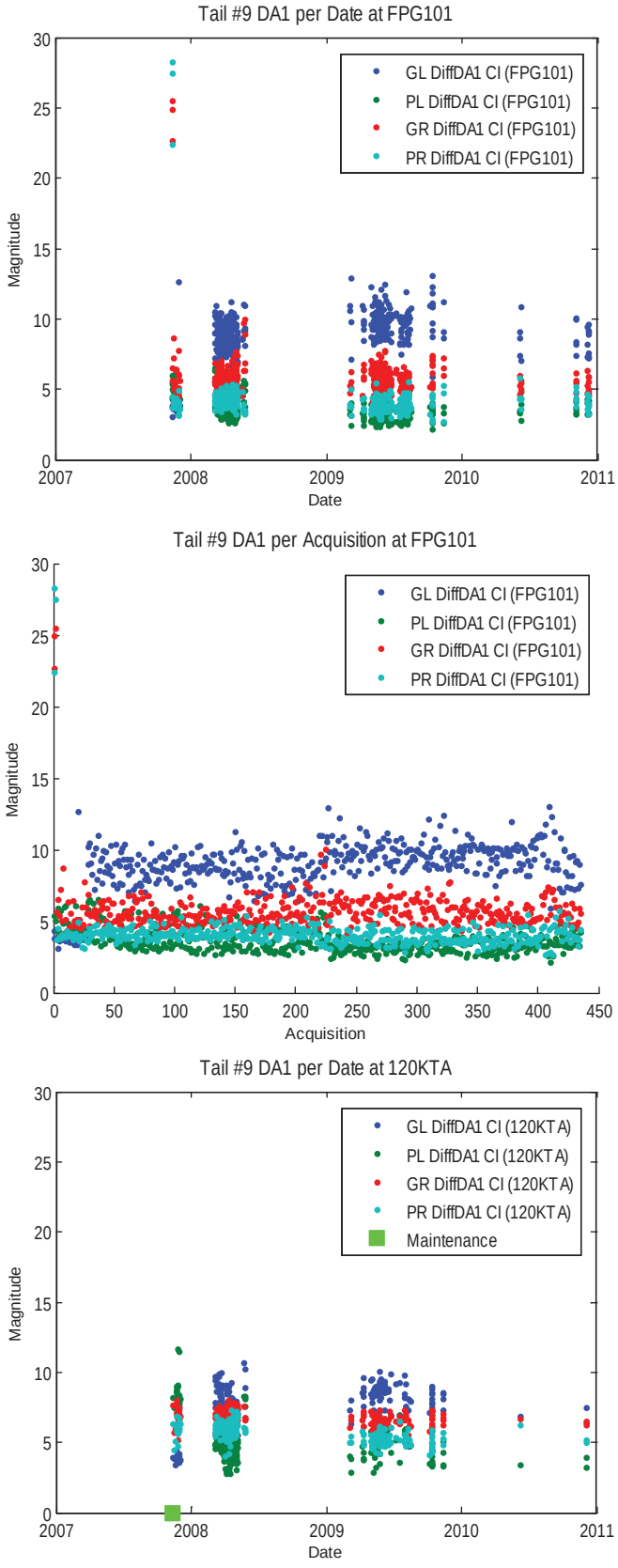

Figure A.9.5.—Tail Number 9 Plots of DiffDA1 per Date, Acquisition and Regime

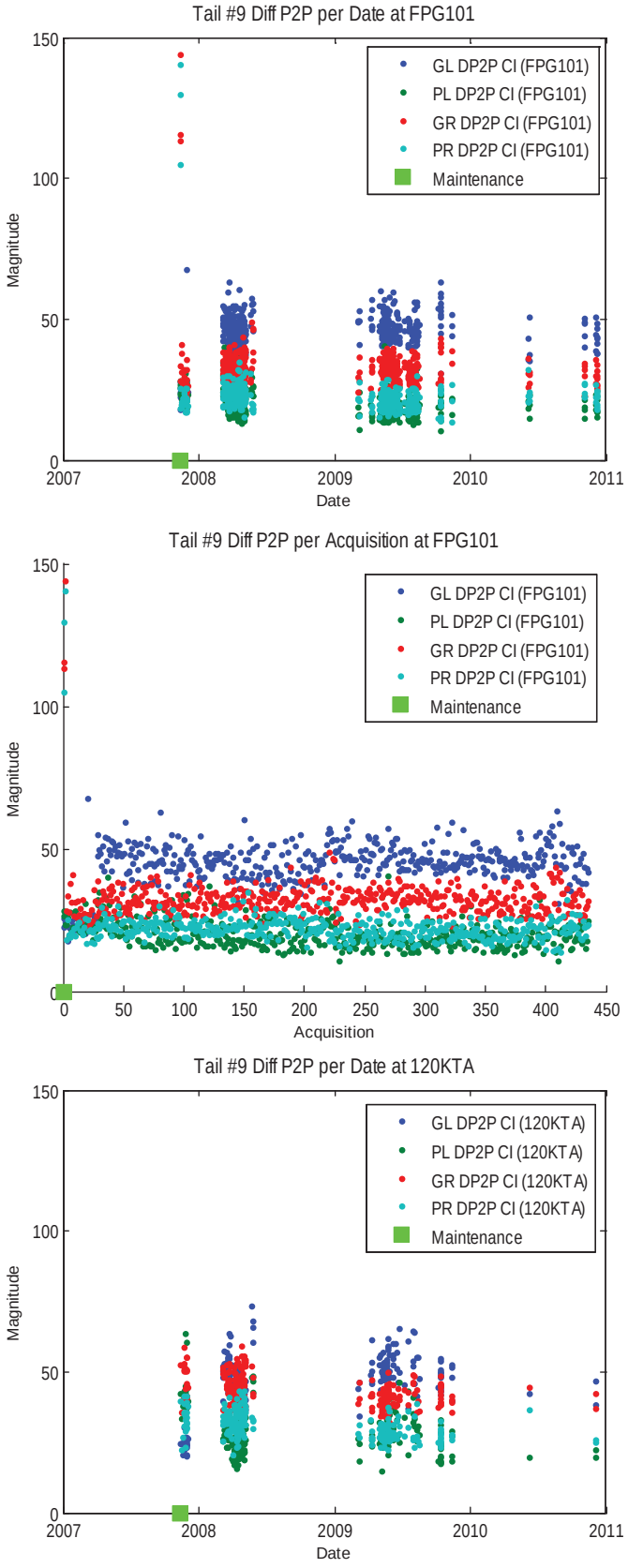

Figure A.9.6.—Tail Number 9 Plots of DP2P per Date, Acquisition and Regime

A.10 Tail Number 10

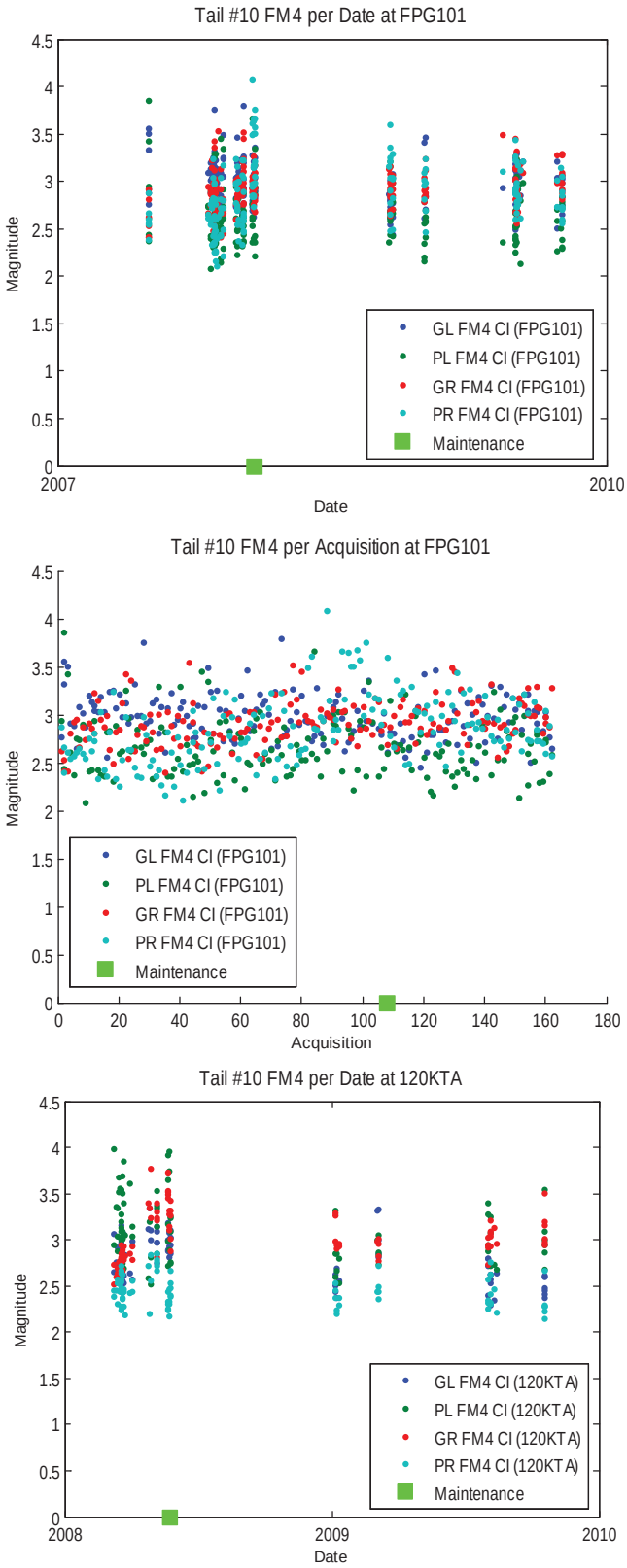

Figure A.10.1.—Tail Number 10 Plots of FM4 per Date, Acquisition and Regime

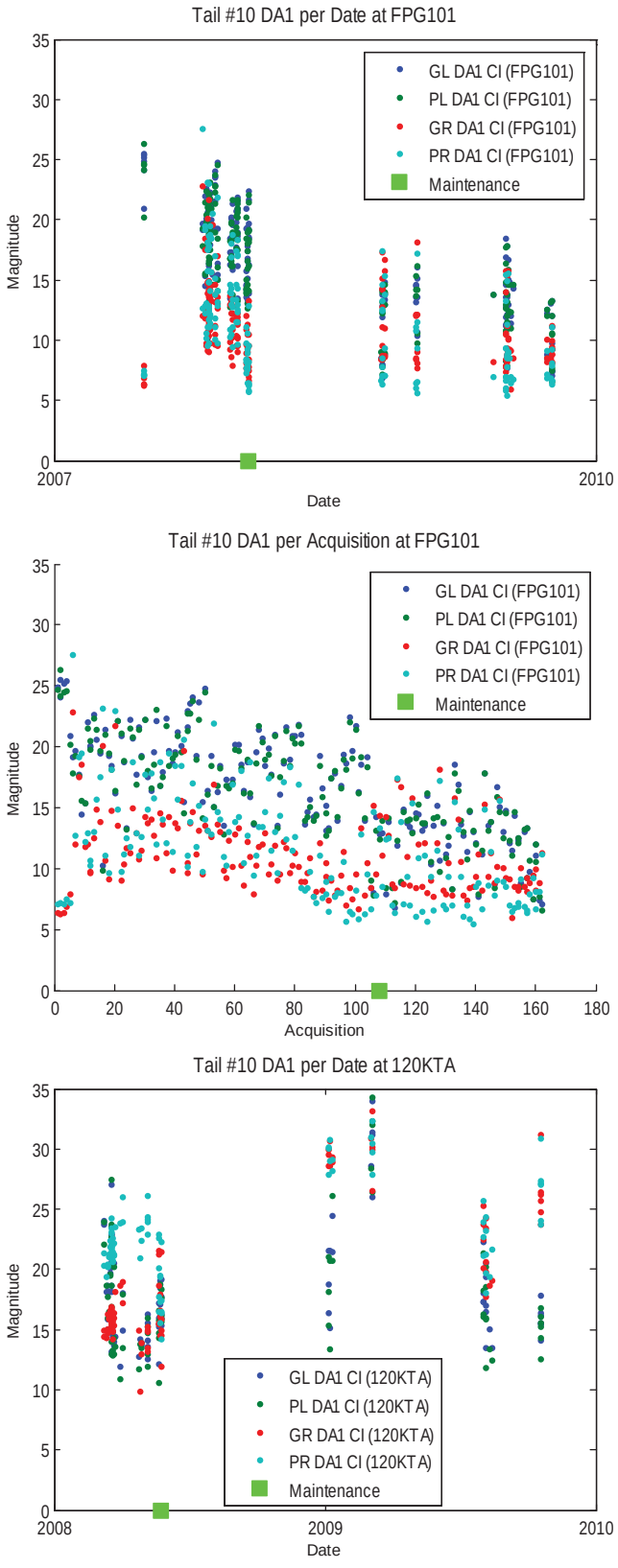

Figure A.10.2.—Tail Number 10 Plots of DA1 per Date, Acquisition and Regime

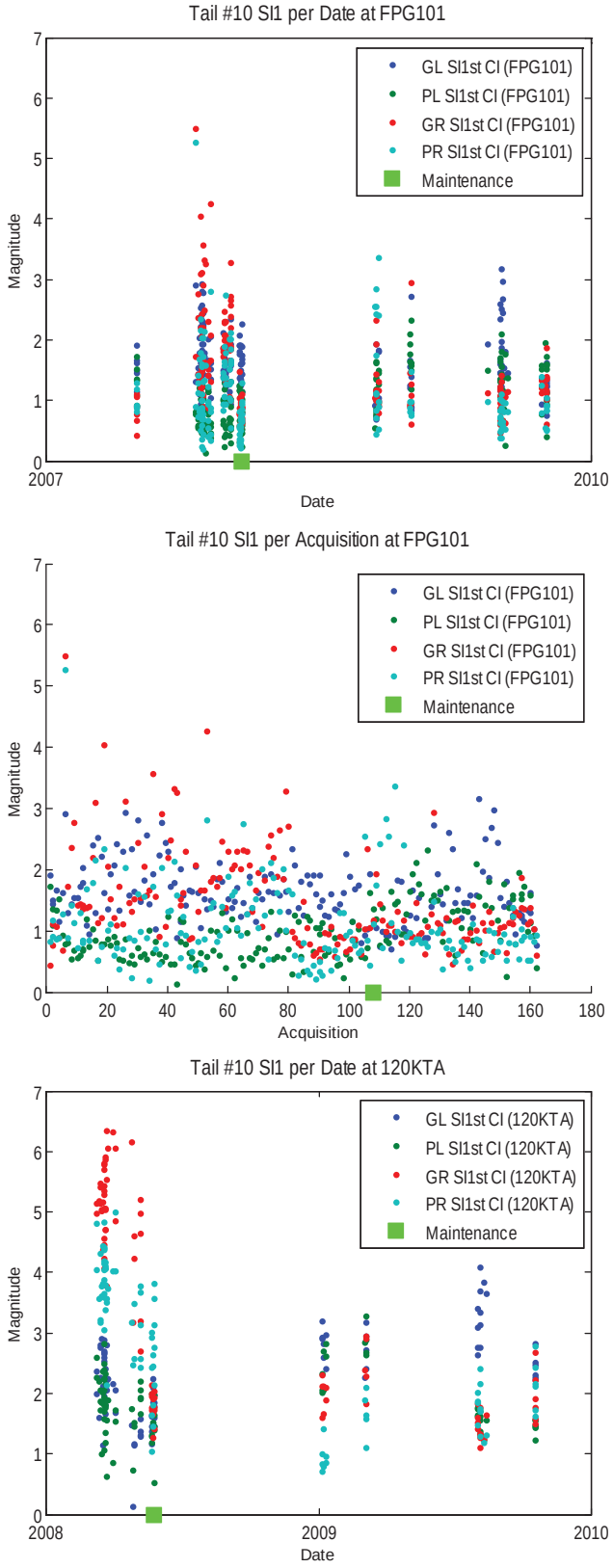

Figure A.10.3.—Tail Number 10 Plots of SI1 per Date, Acquisition and Regime

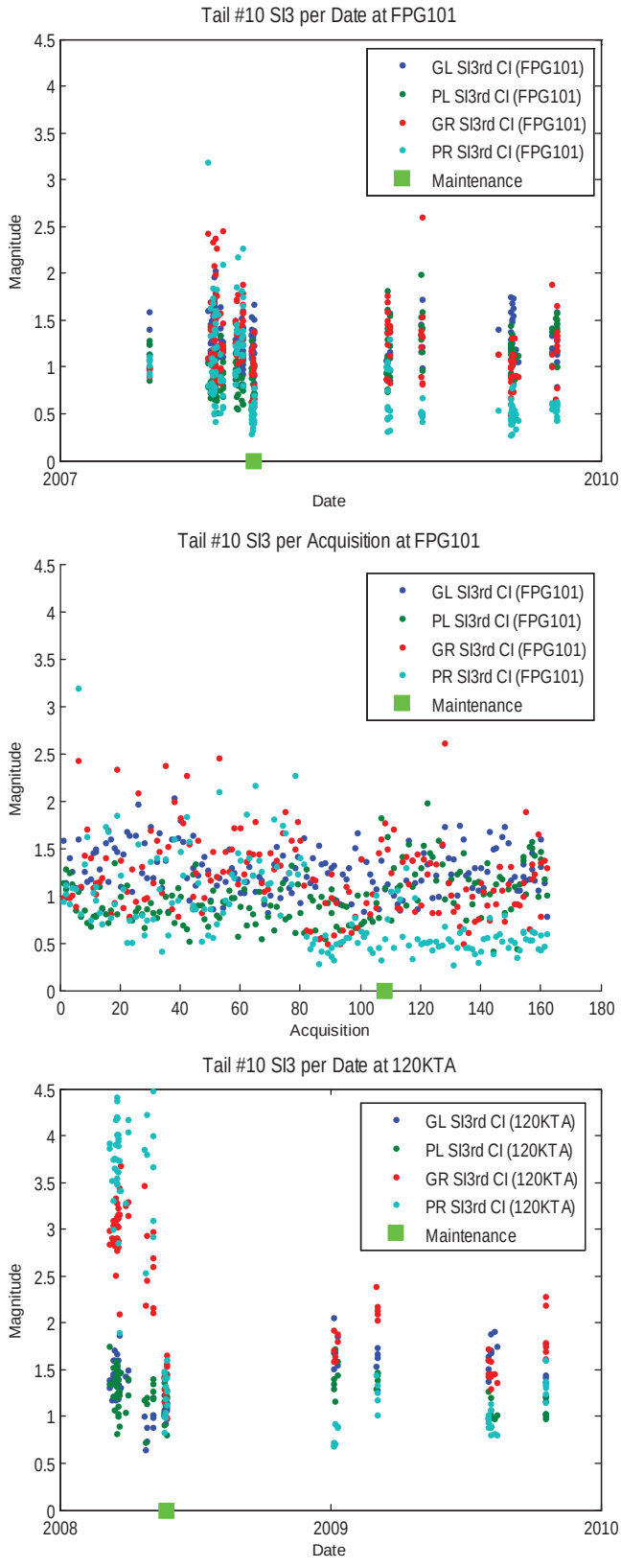

Figure A.10.4.—Tail Number 10 Plots of SI3 per Date, Acquisition and Regime

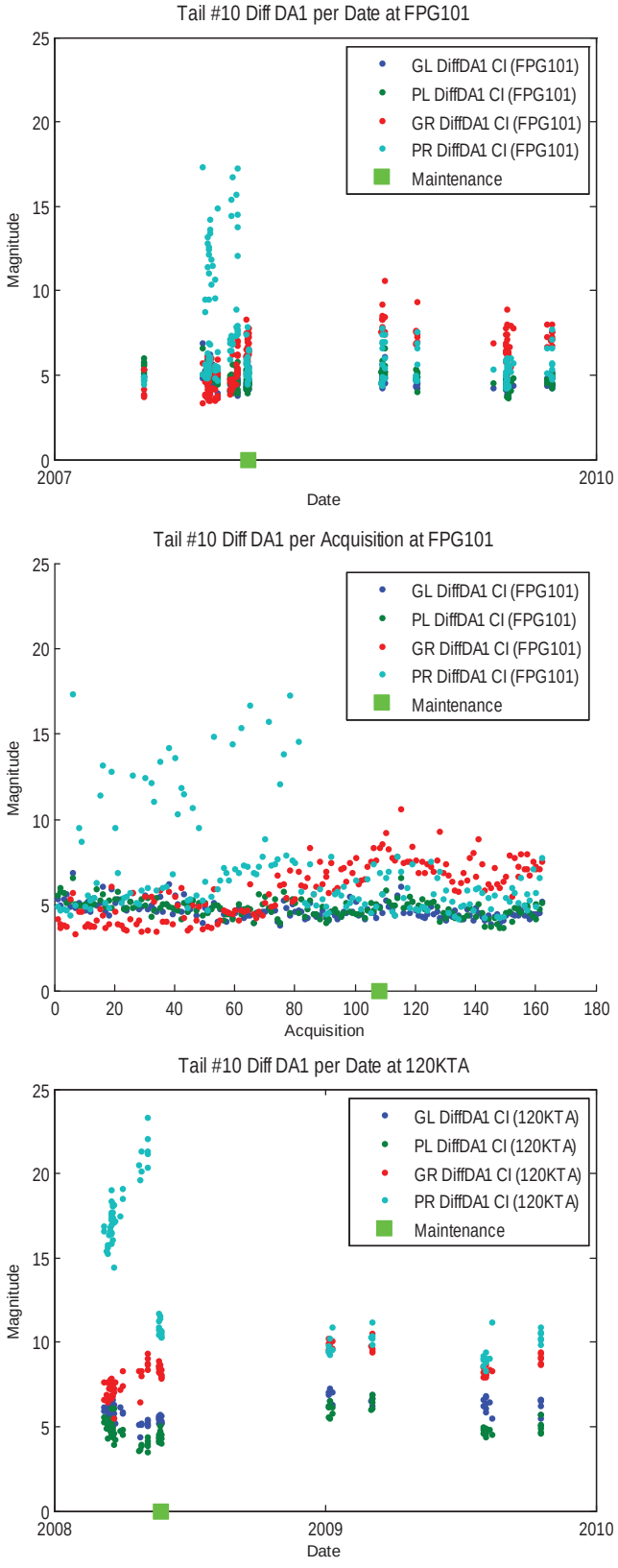

Figure A.10.5.—Tail Number 10 Plots of DiffDA1 per Date, Acquisition and Regime

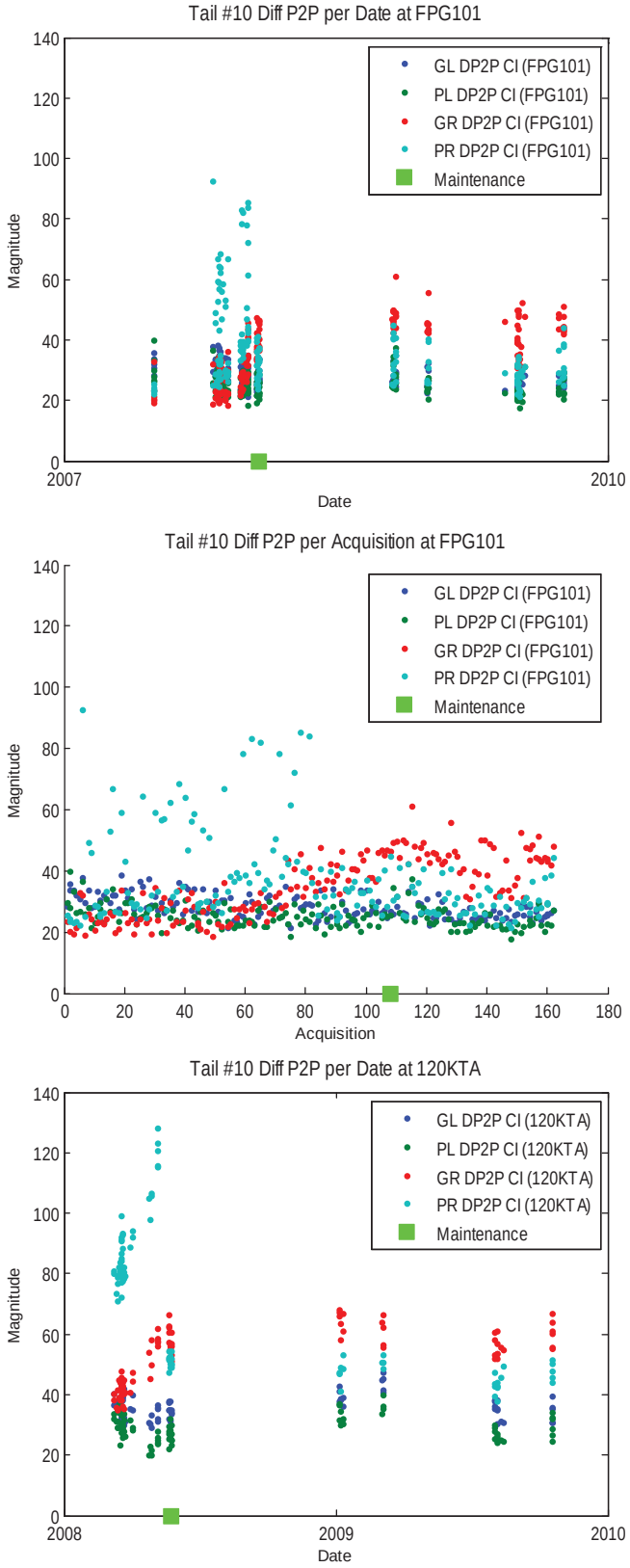

Figure A.10.6.—Tail Number 10 Plots of DP2P per Date, Acquisition and Regime

A.11 Tail Number 11

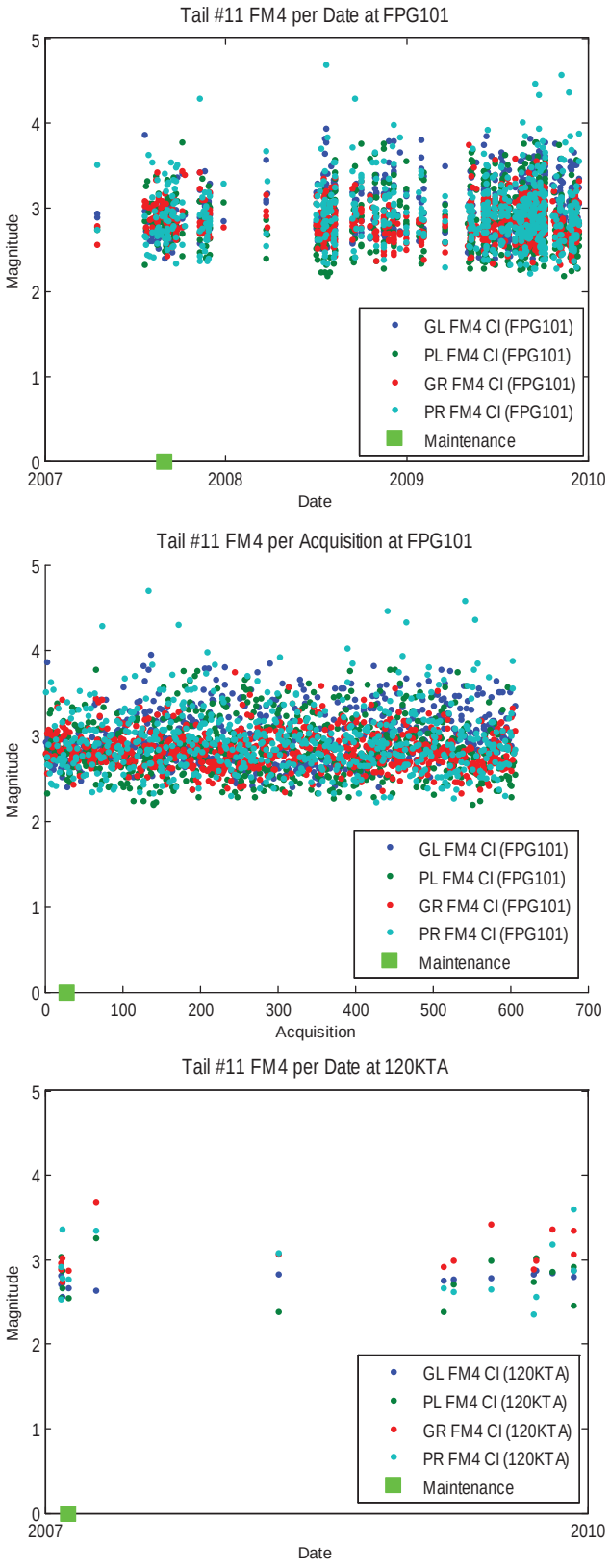

Figure A.11.1.—Tail Number 11 Plots of FM4 per Date, Acquisition and Regime

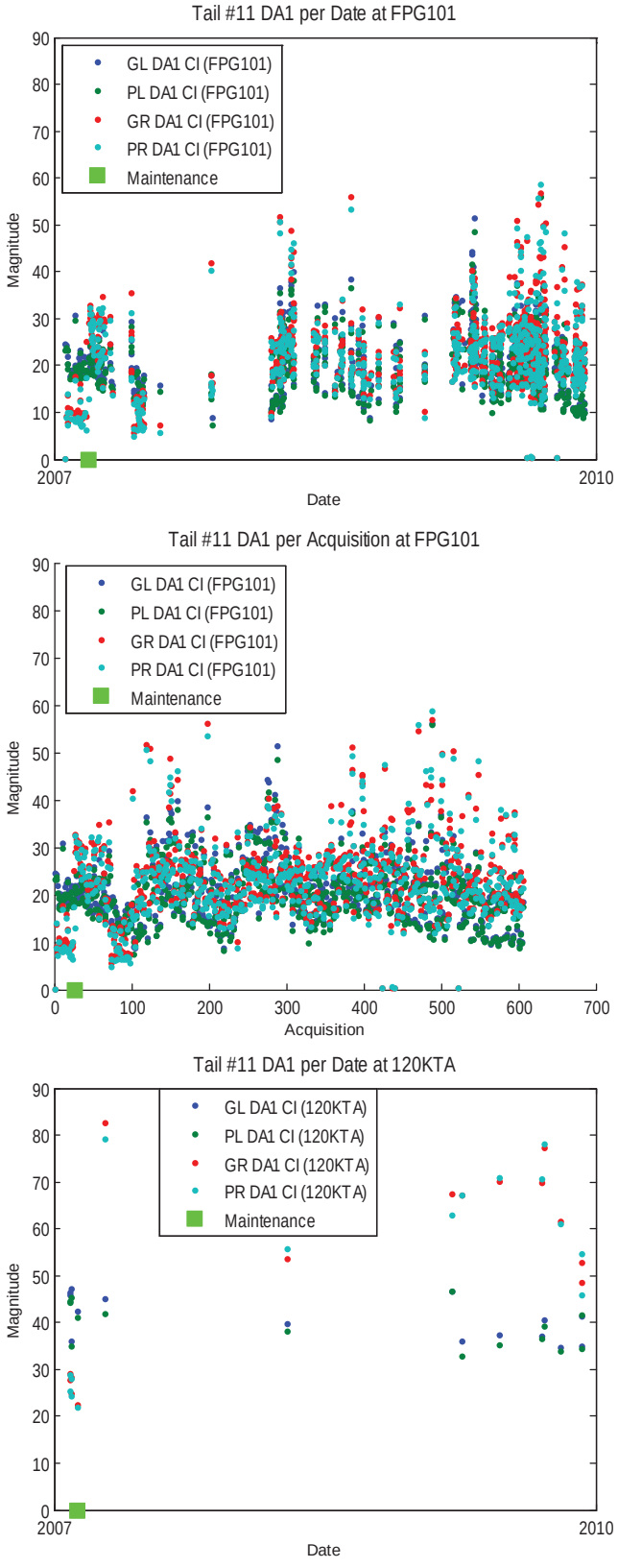

Figure A.11.2.—Tail Number 11 Plots of DA1 per Date, Acquisition and Regime

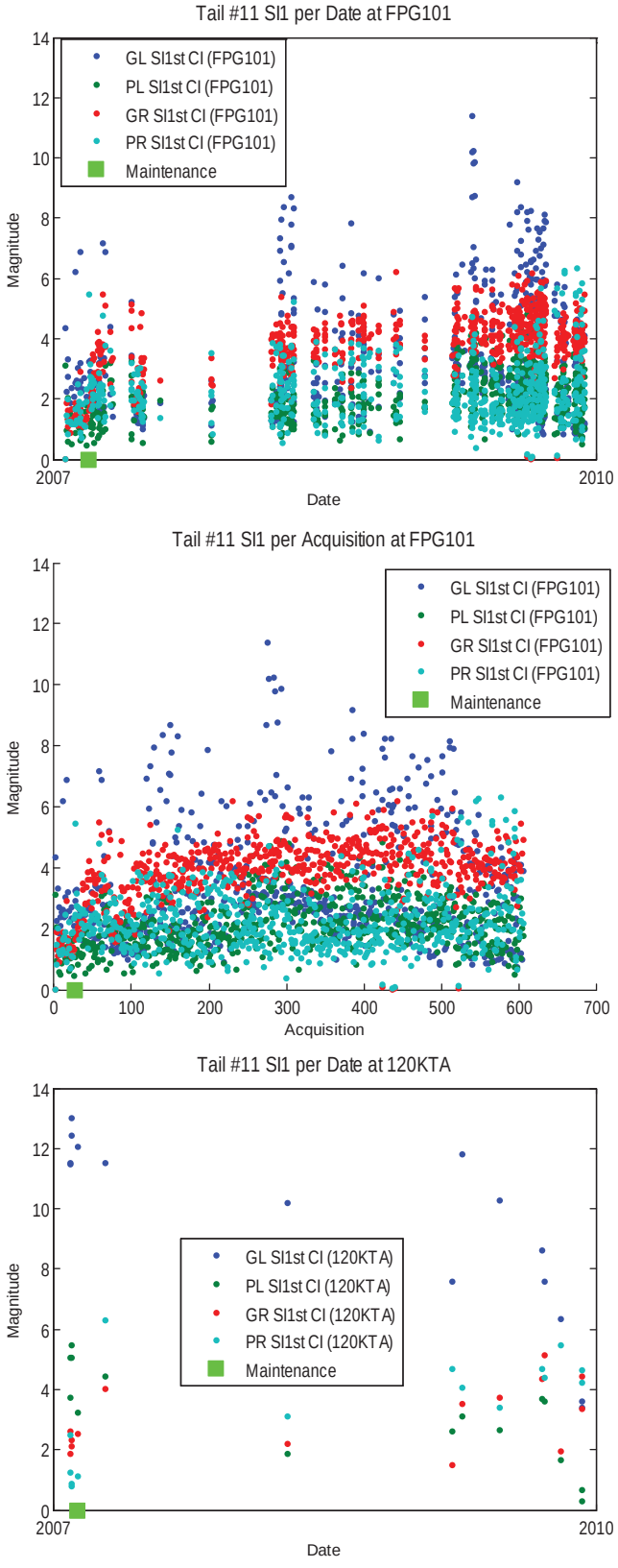

Figure A.11.3.—Tail Number 11 Plots of SI1 per Date, Acquisition and Regime

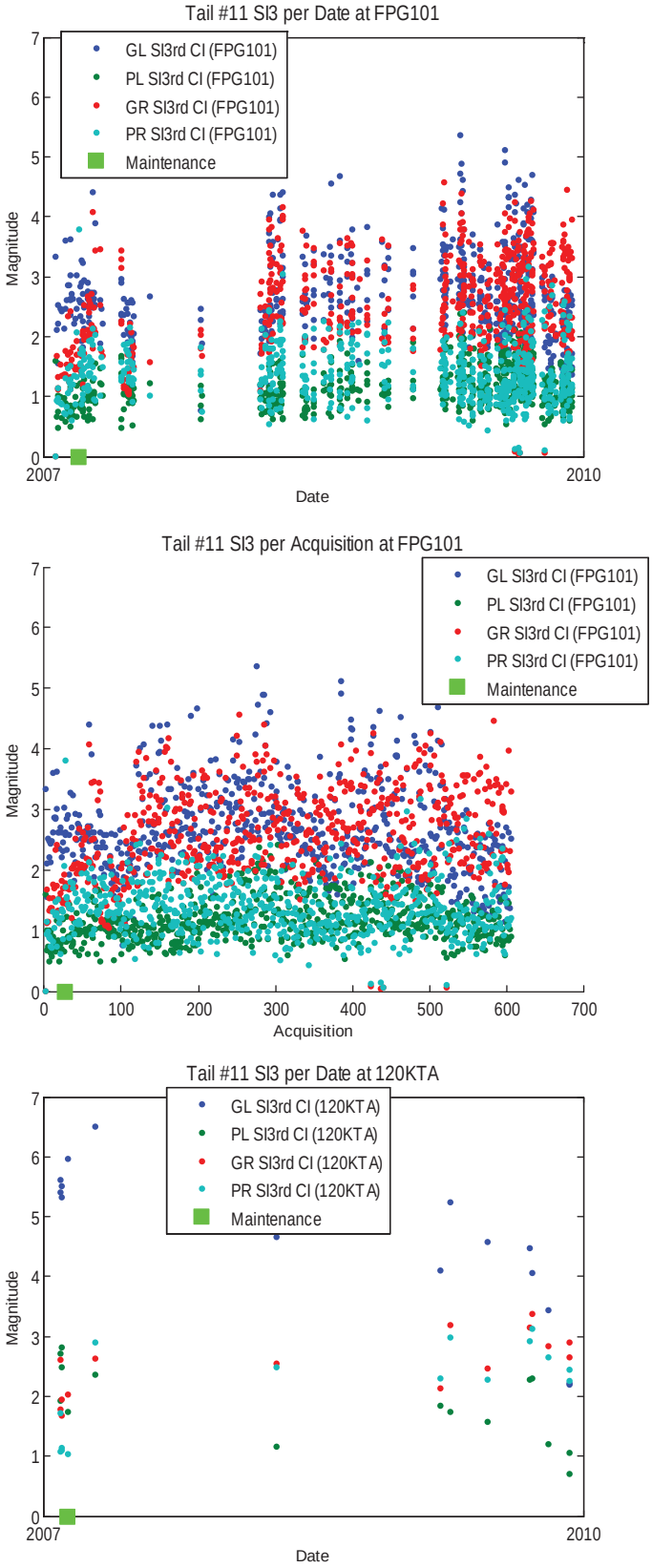

Figure A.11.4.—Tail Number 11 Plots of SI3 per Date, Acquisition and Regime

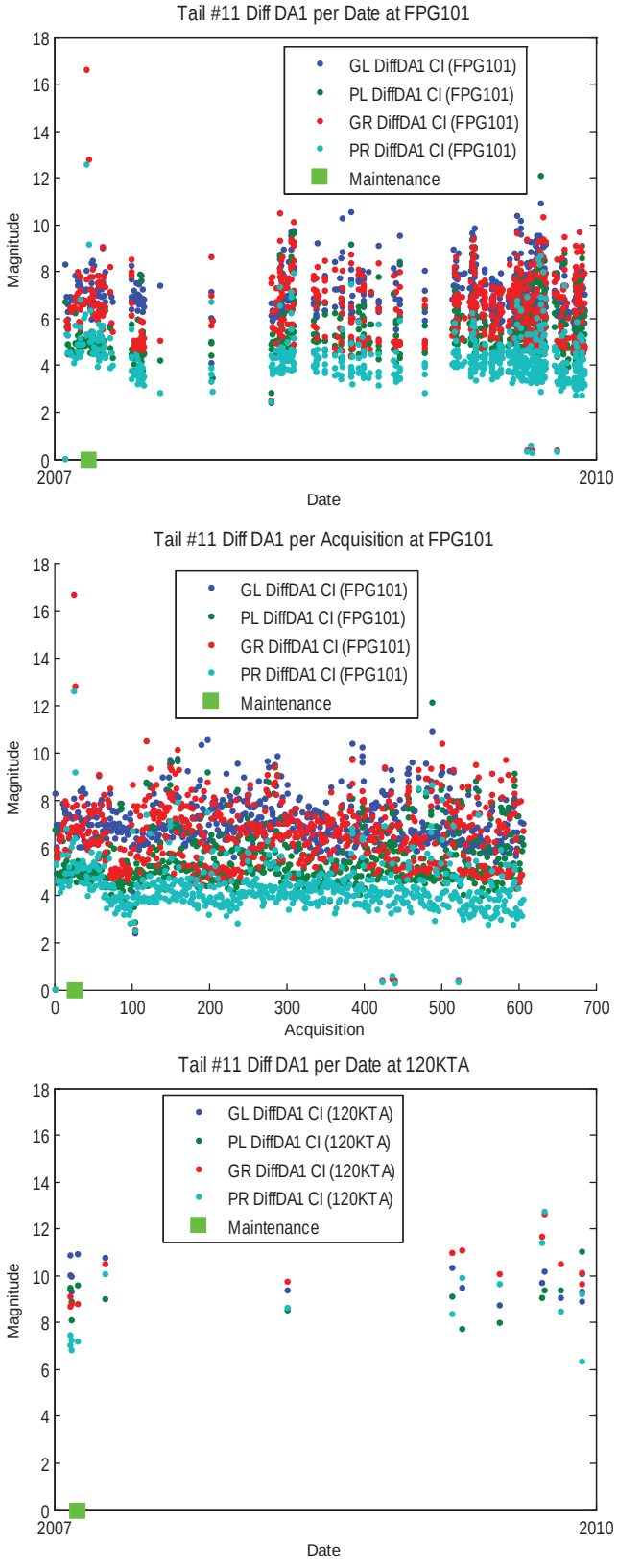

Figure A.11.5.—Tail Number 11 Plots of DiffDA1 per Date, Acquisition and Regime

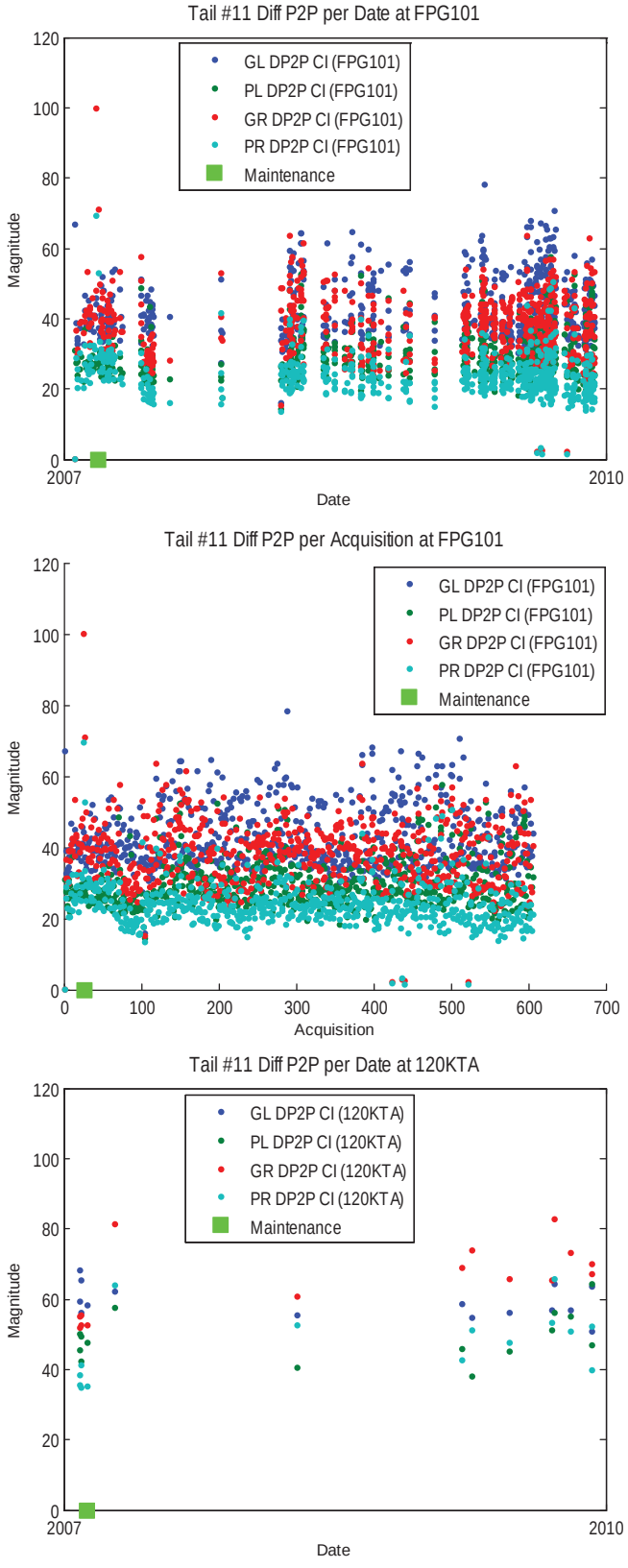

Figure A.11.6.—Tail Number 11 Plots of DP2P per Date, Acquisition and Regime

A.12 Tail Number 12

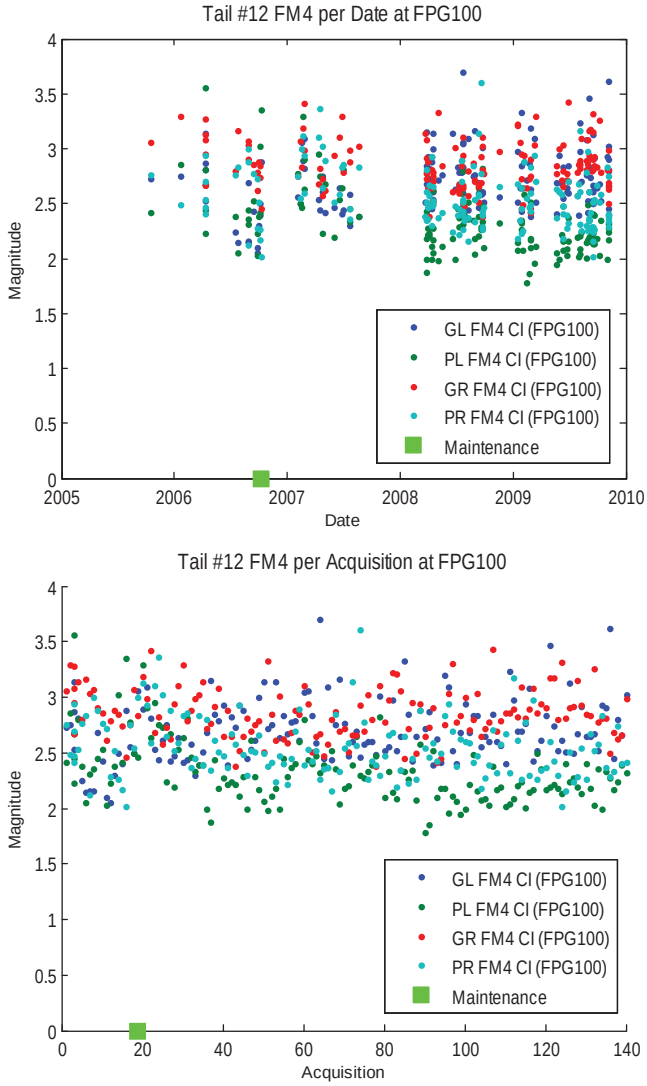

Figure A.12.1.—Tail Number 12 Plots of FM4 per Date and Acquisition

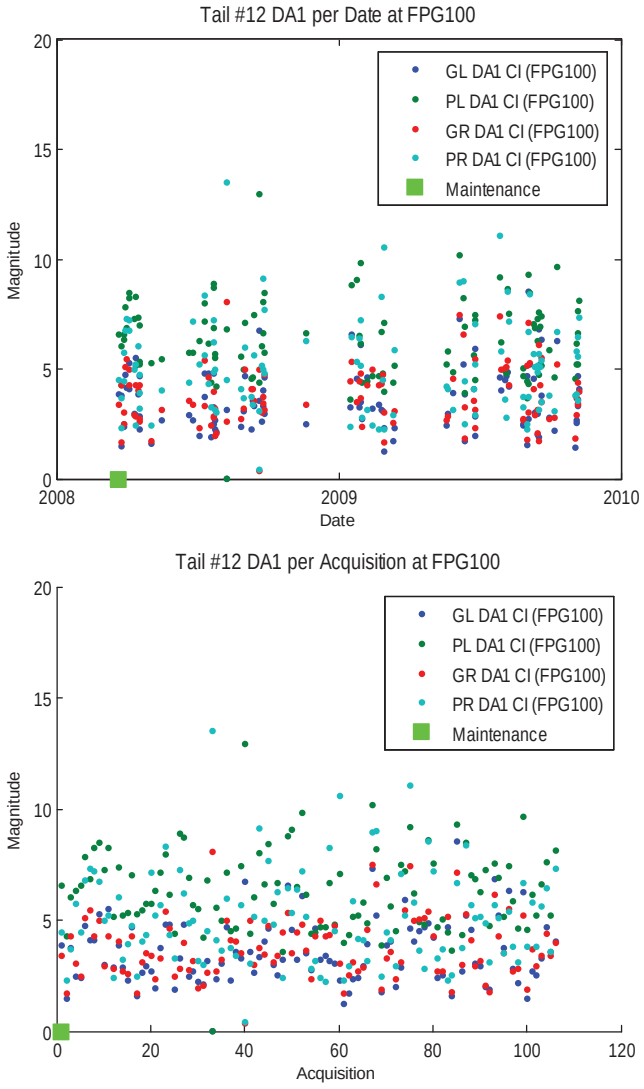

Figure A.12.2.—Tail Number 12 Plots of DA1 per Date and Acquisition

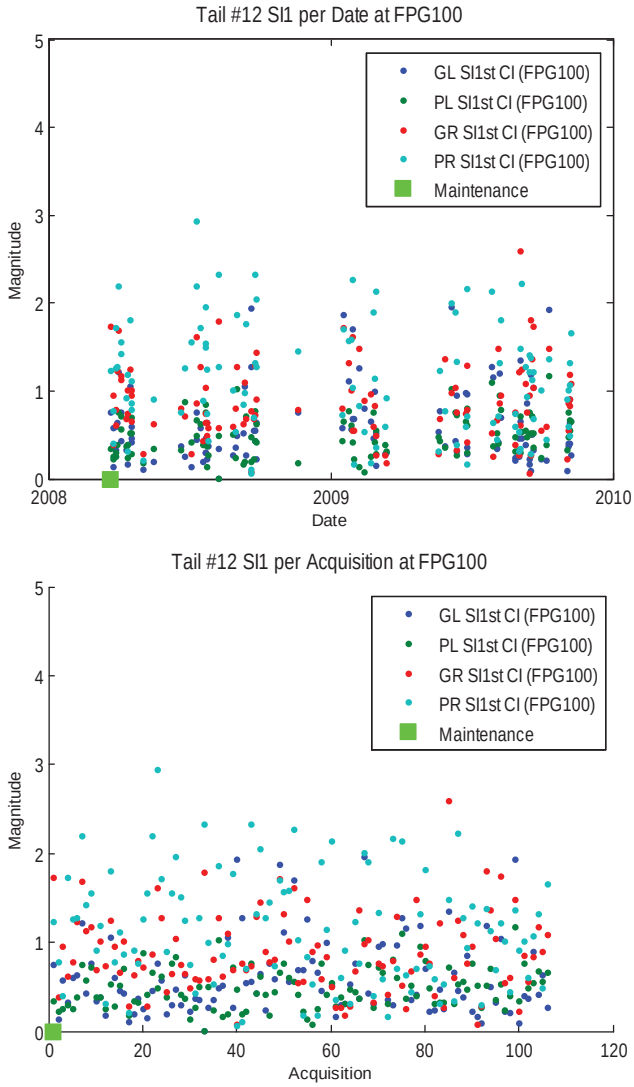

Figure A.12.3.—Tail Number 12 Plots of Sl1 per Date and Acquisition

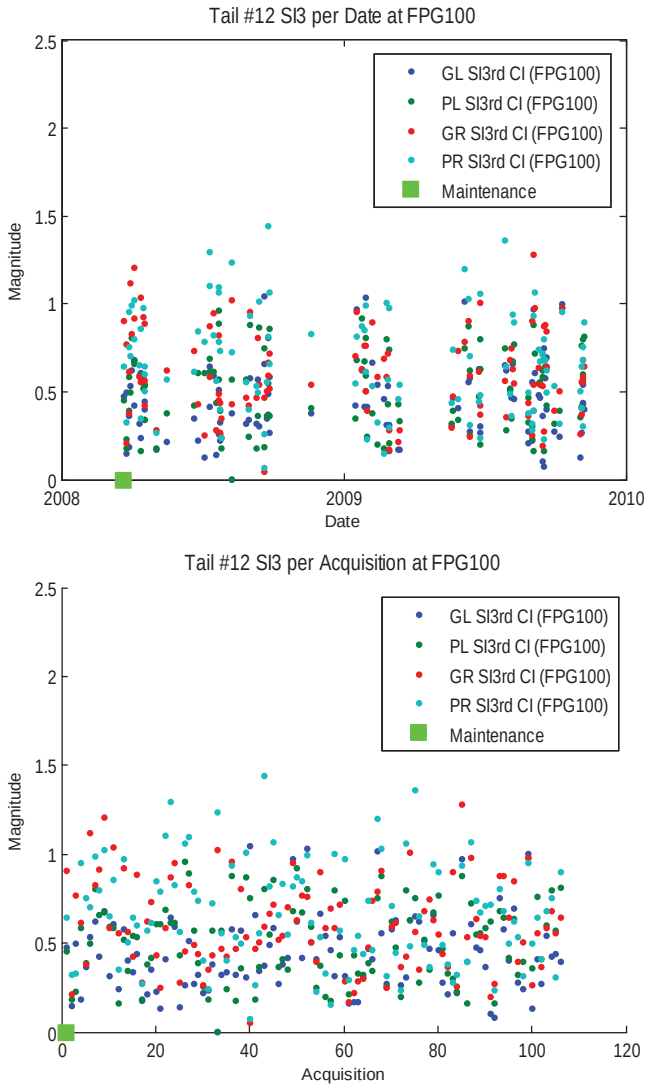

Figure A.12.4.—Tail Number 12 Plots of SI3 per Date and Acquisition

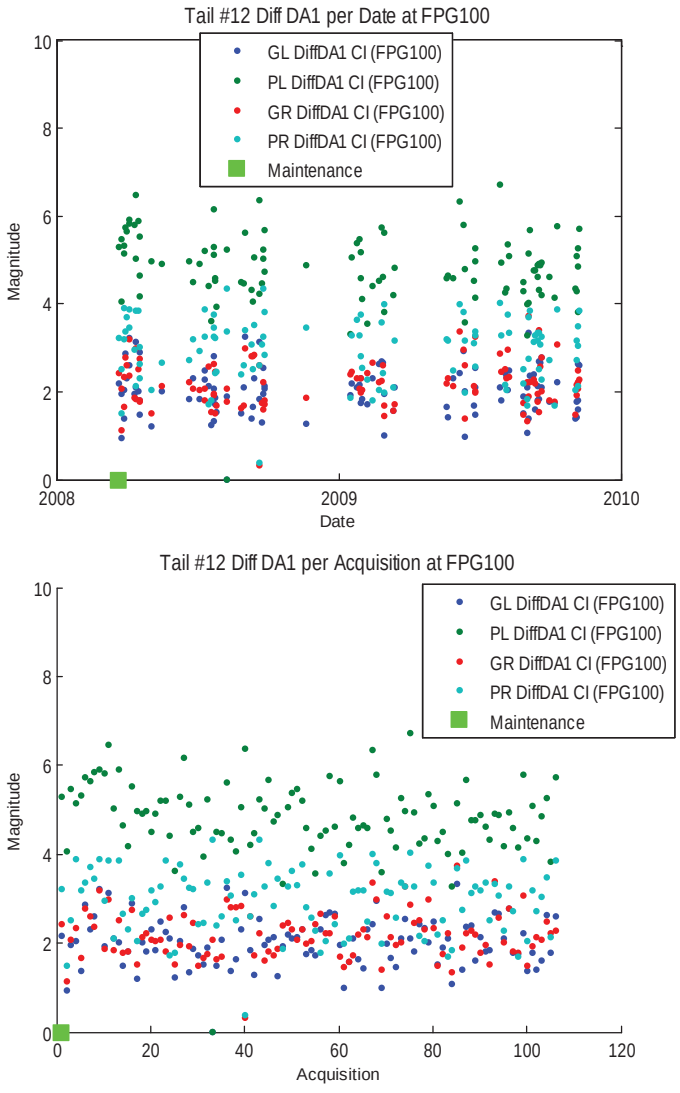

Figure A.12.5.—Tail Number 12 Plots of DiffDA1 per Date and Acquisition

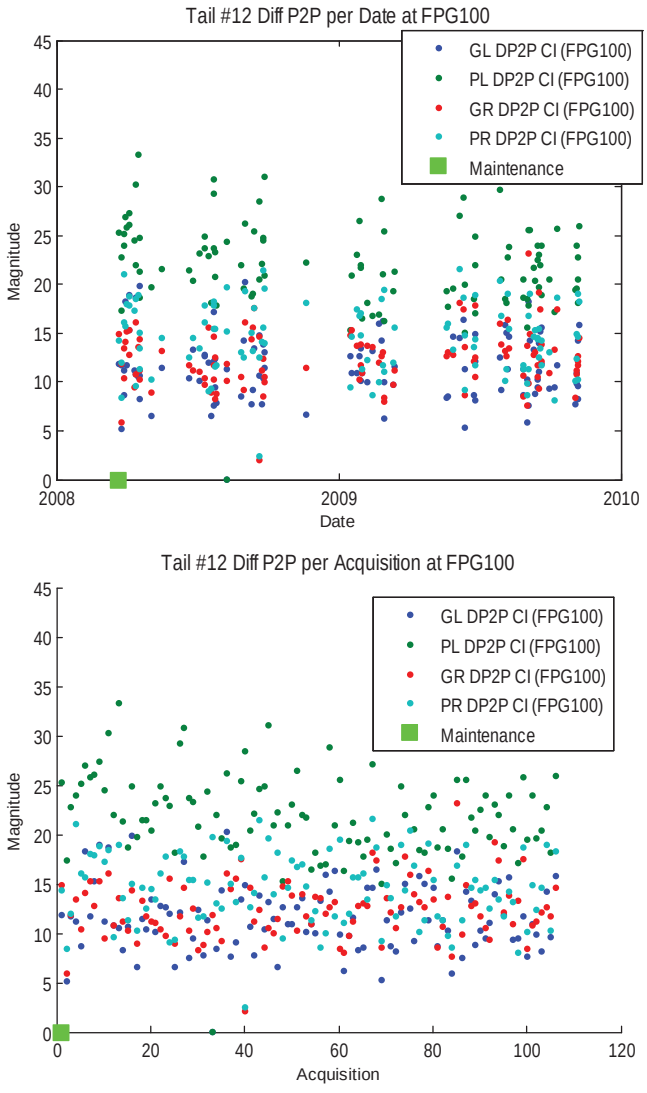

Figure A.12.6.—Tail Number 12 Plots of DP2P per Date and Acquisition

A.13 Tail Number 13

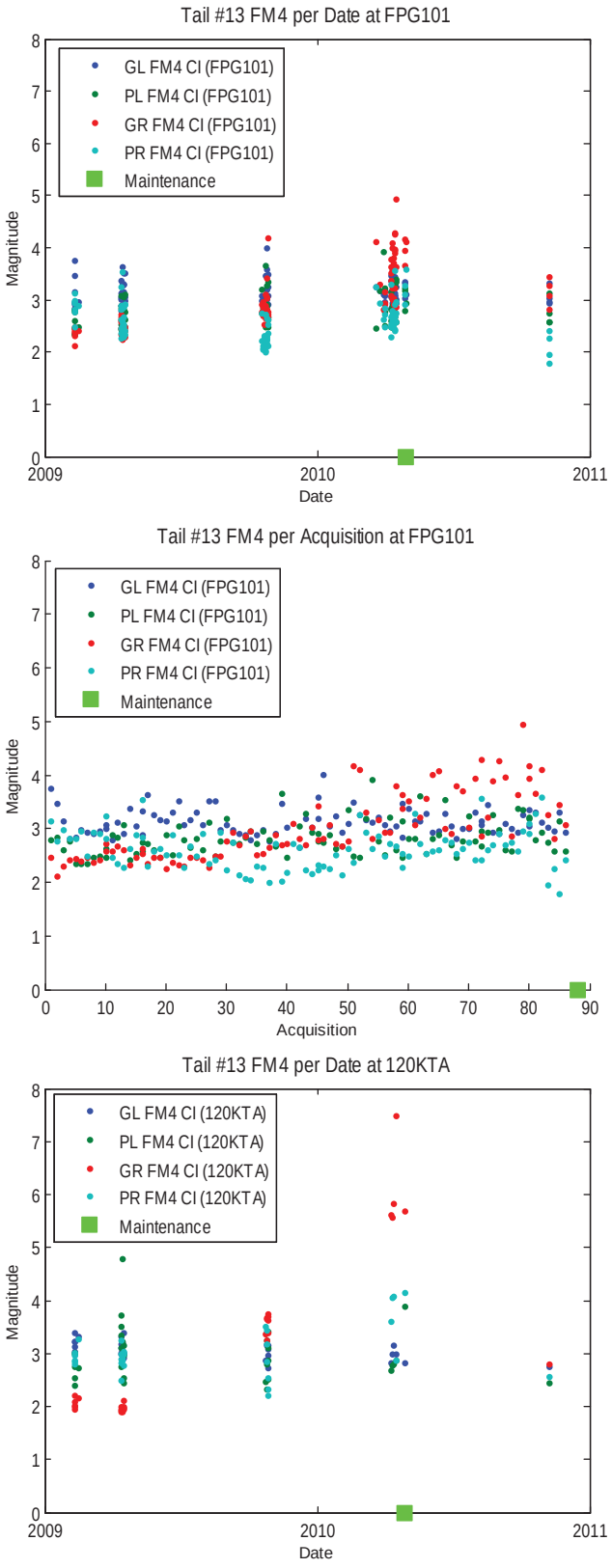

Figure A.13.1.—Tail Number 13 Plots of FM4 per Date, Acquisition and Regime

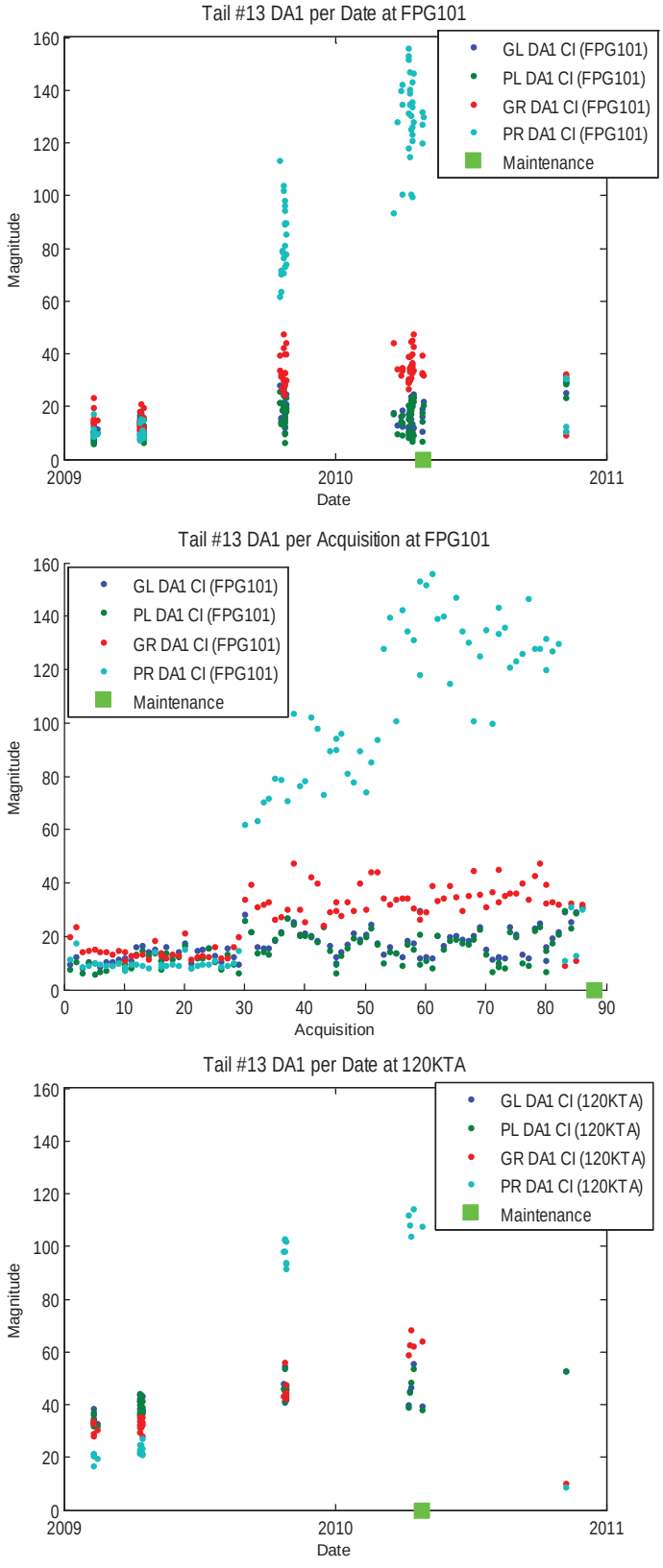

Figure A.13.2.—Tail Number 13 Plots of DA1 per Date, Acquisition and Regime

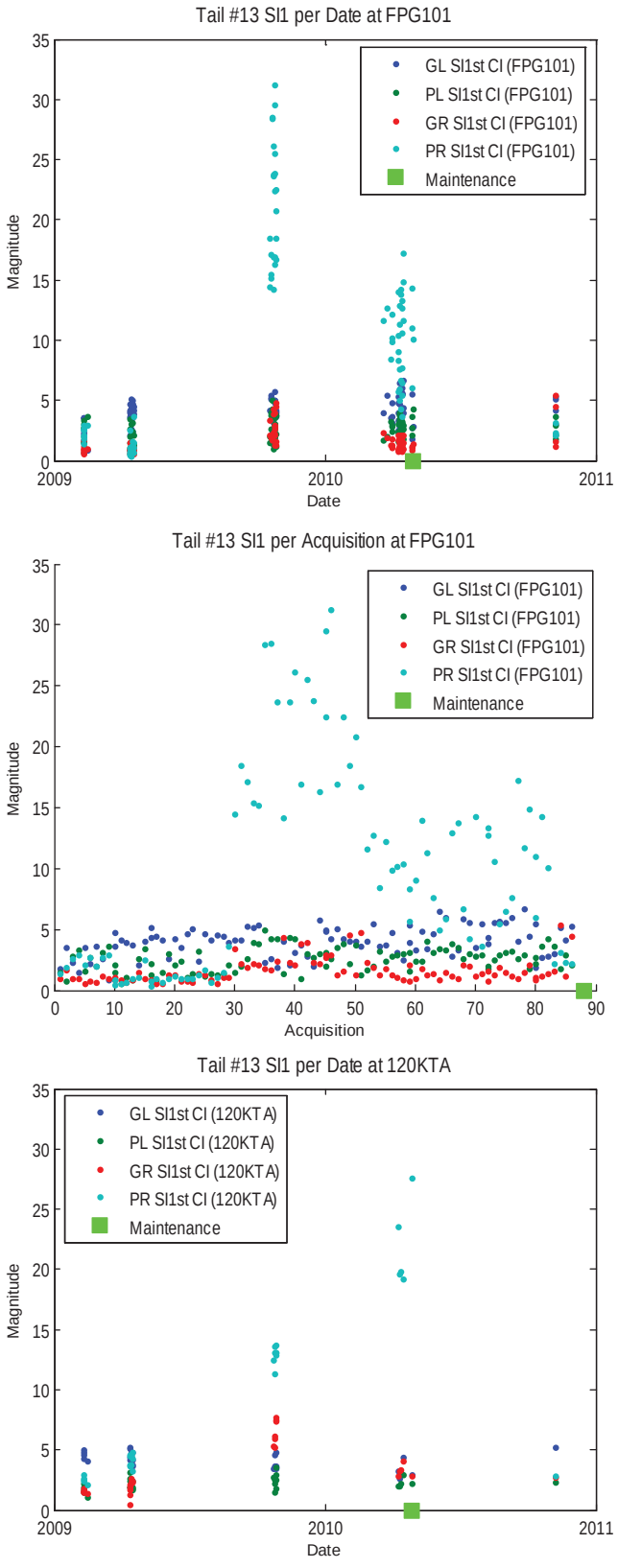

Figure A.13.3.—Tail Number 13 Plots of SI1 per Date, Acquisition and Regime

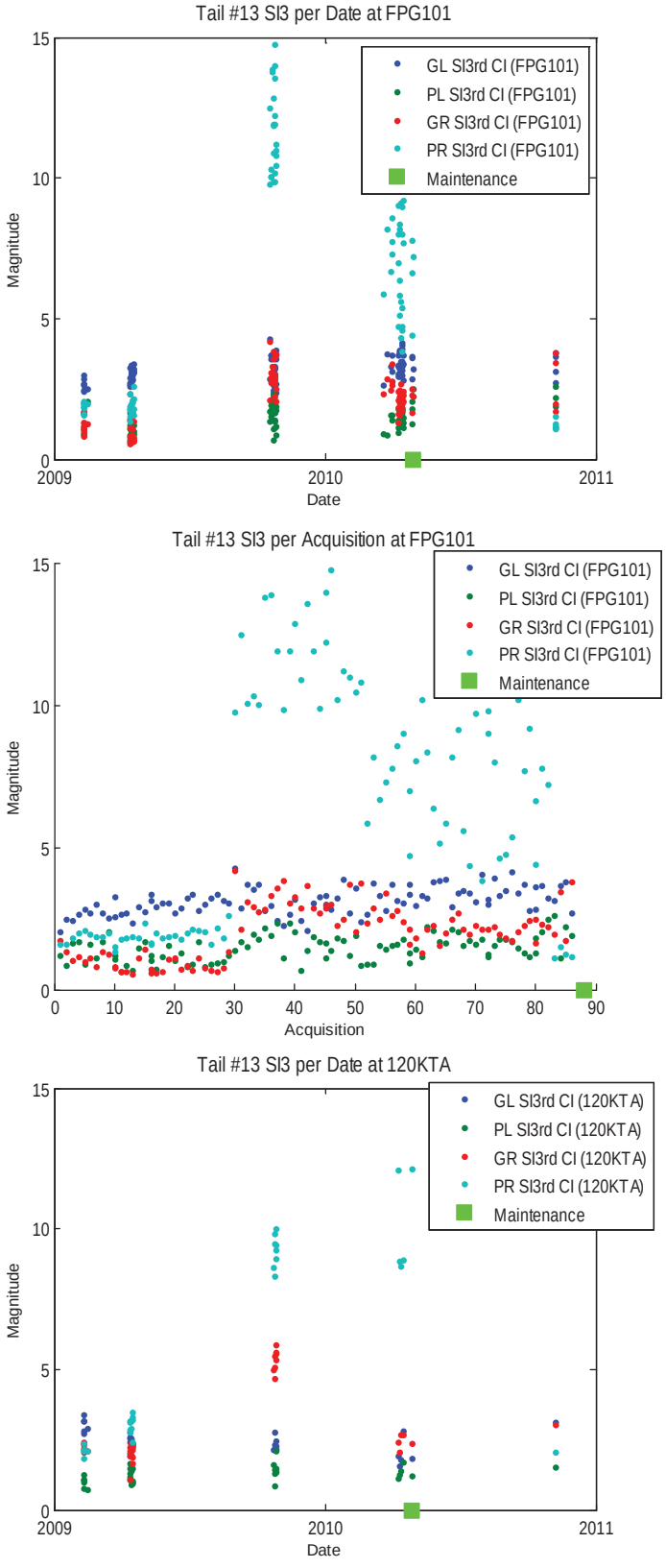

Figure A.13.4.—Tail Number 13 Plots of SI3 per Date, Acquisition and Regime

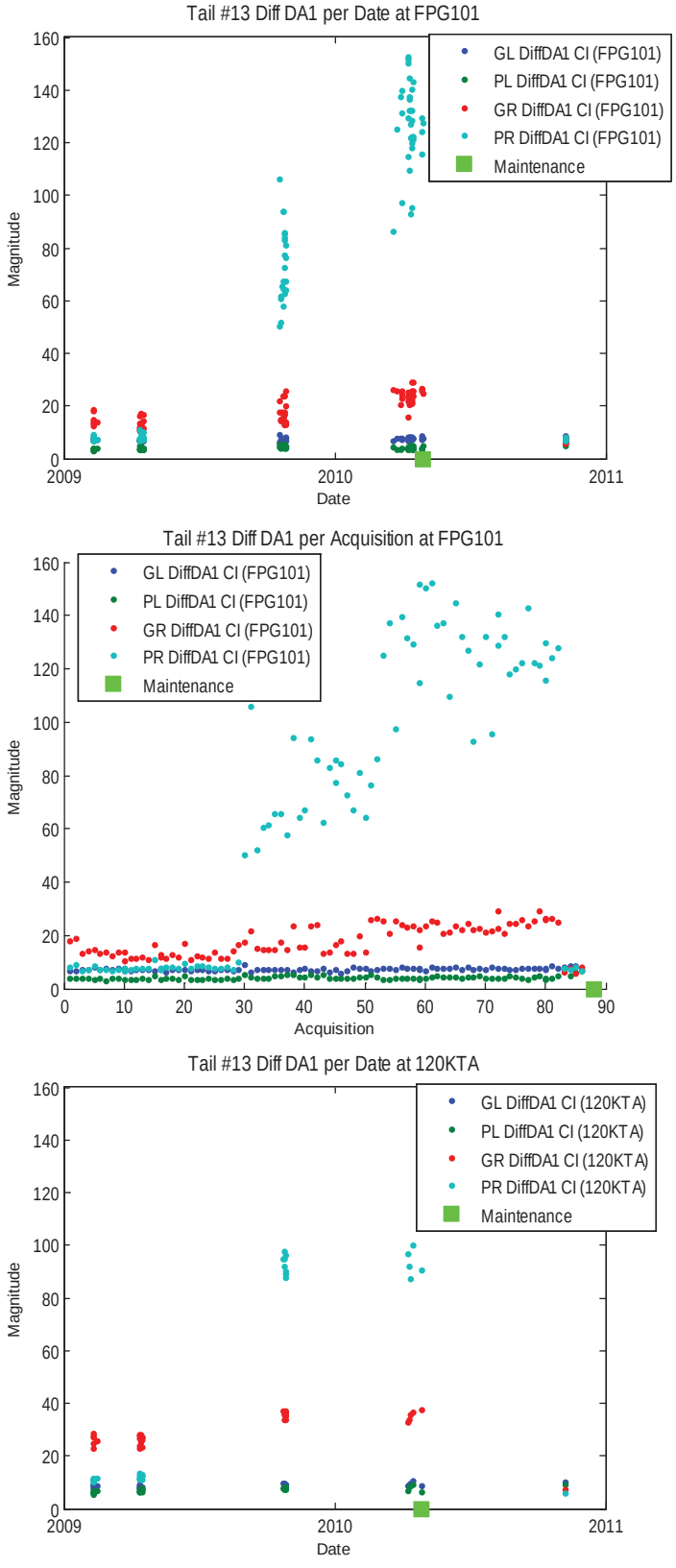

Figure A.13.5.—Tail Number 13 Plots of DiffDA1 per Date, Acquisition and Regime

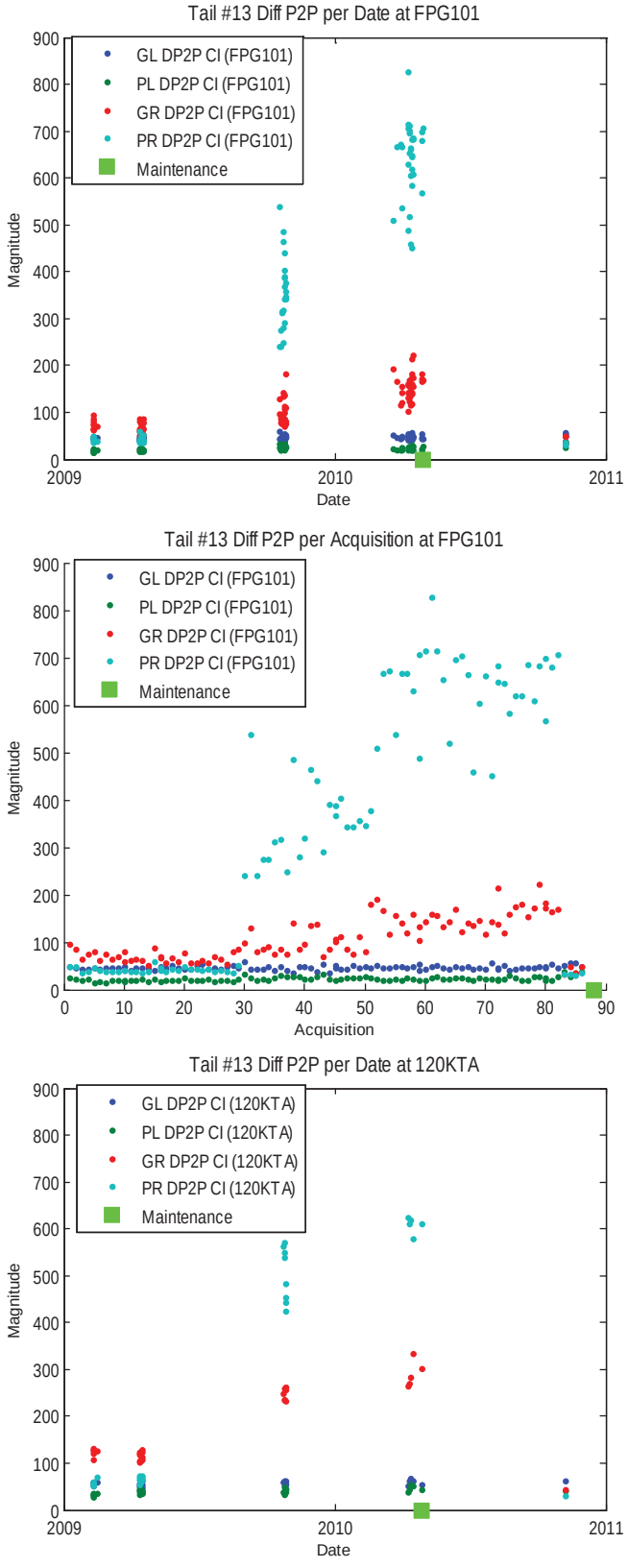

Figure A.13.6.—Tail Number 13 Plots of DP2P per Date, Acquisition and Regime

A.14 Tail Number 14

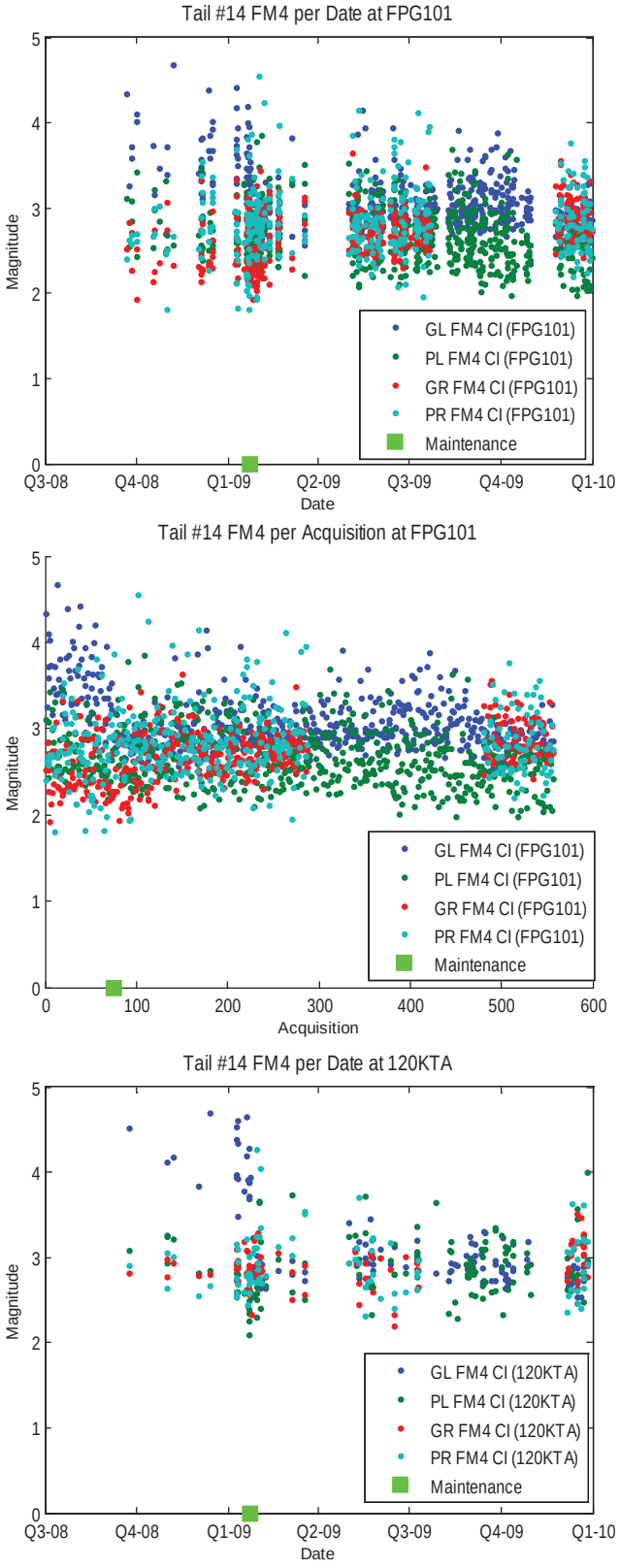

Figure A.14.1.—Tail Number 14 Plots of FM4 per Date, Acquisition and Regime

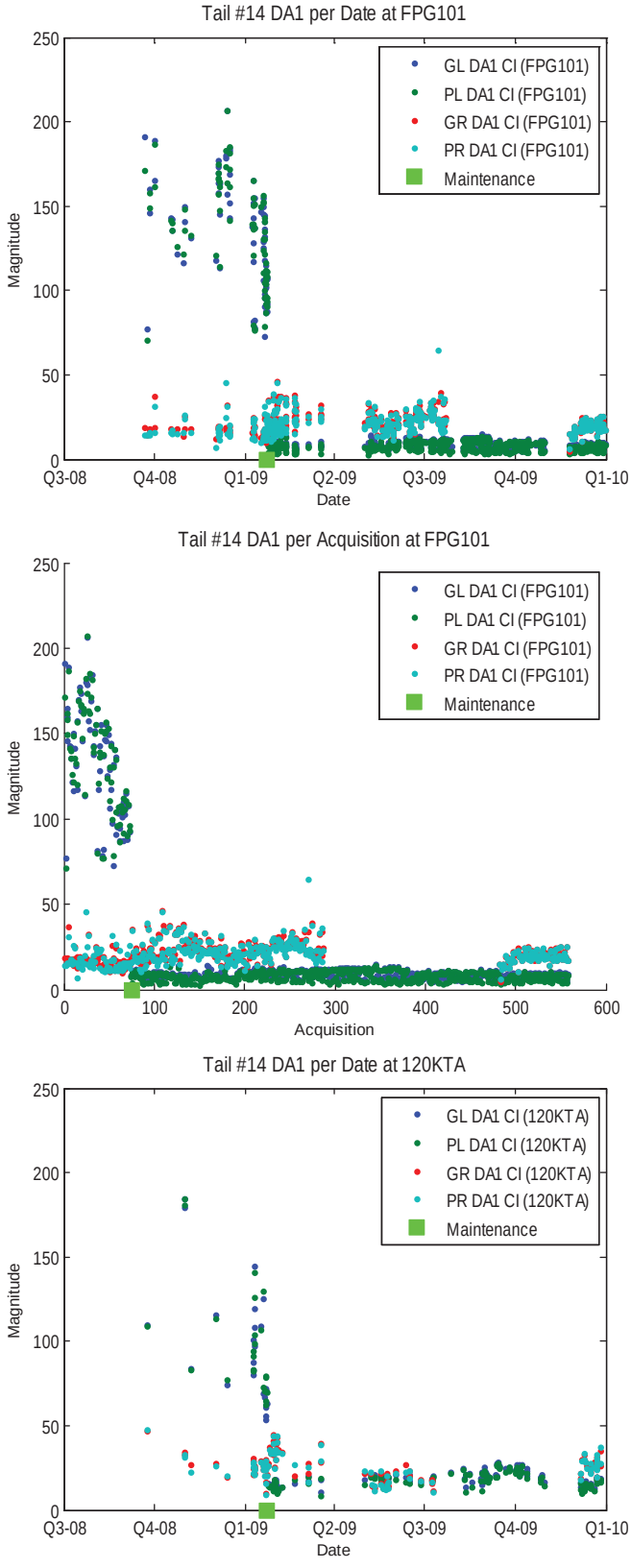

Figure A.14.2.—Tail Number 14 Plots of DA1 per Date, Acquisition and Regime

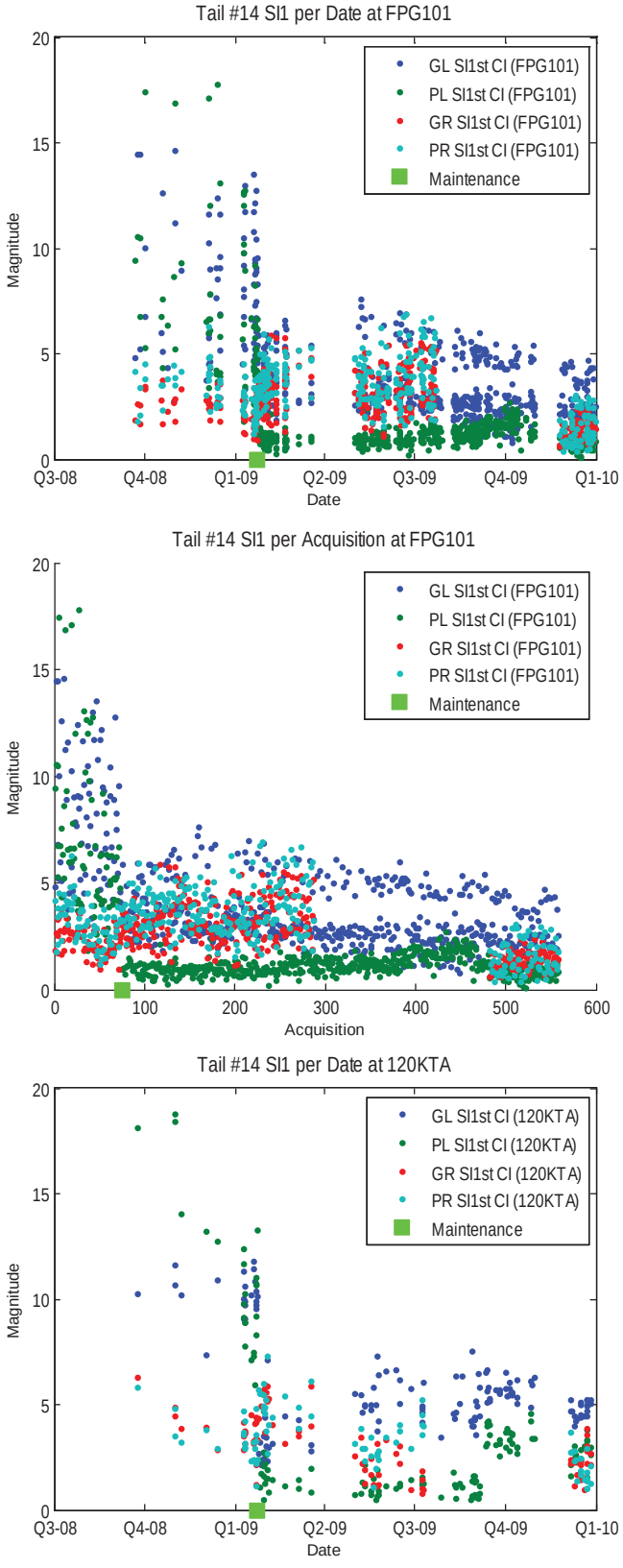

Figure A.14.3.—Tail Number 14 Plots of SI1 per Date, Acquisition and Regime

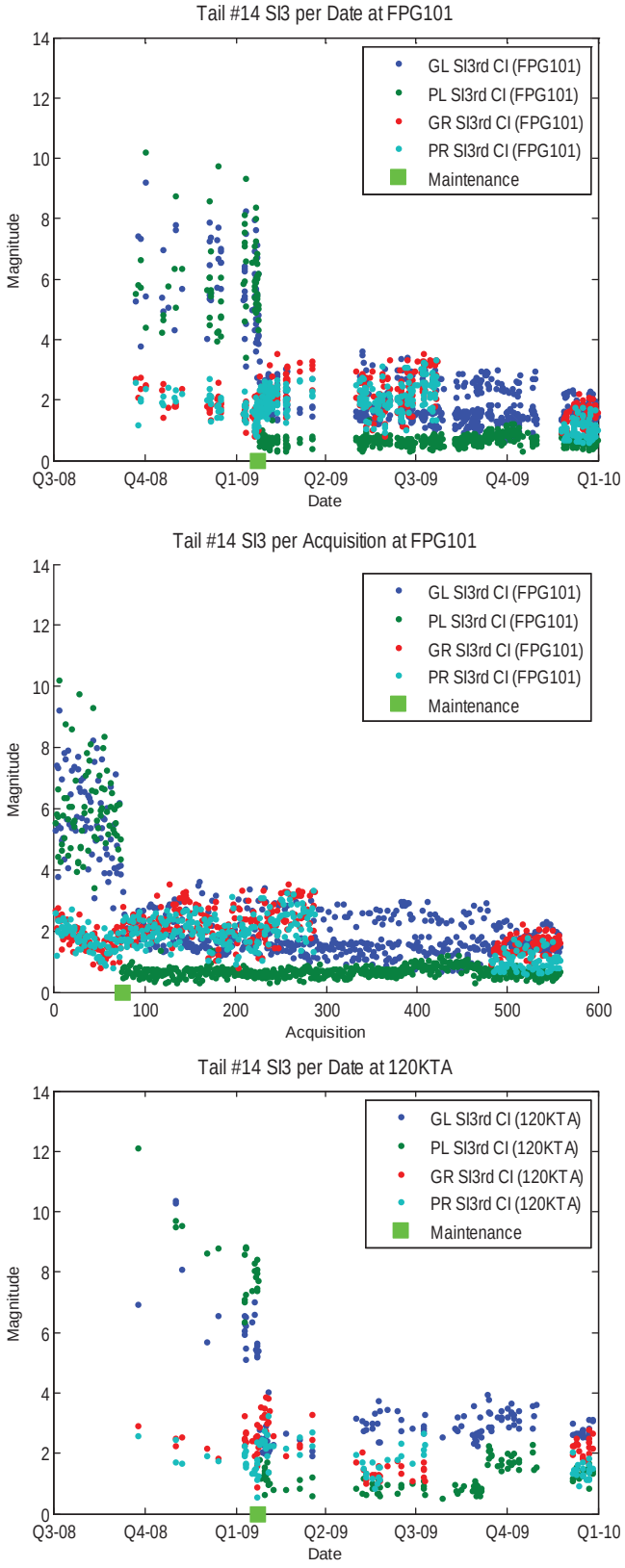

Figure A.14.4.—Tail Number 14 Plots of SI3 per Date, Acquisition and Regime

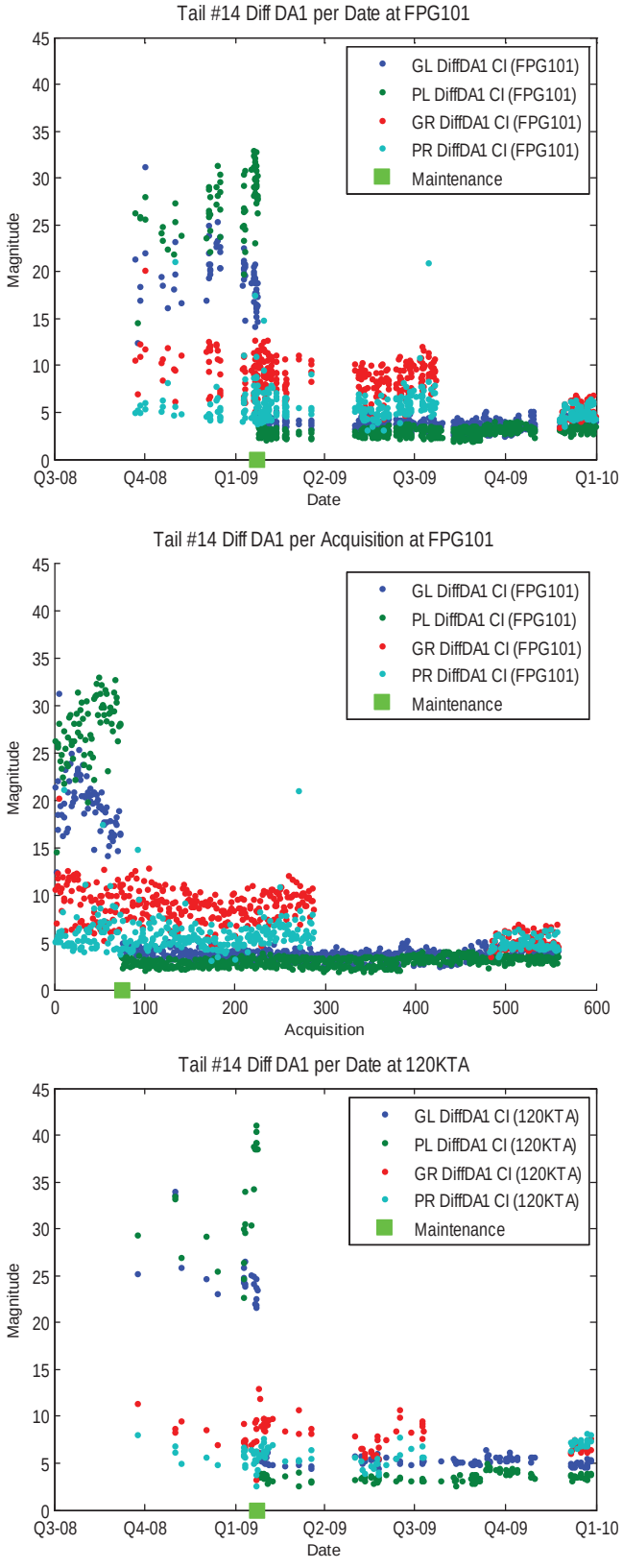

Figure A.14.5.—Tail Number 14 Plots of DiffDA1 per Date, Acquisition and Regime

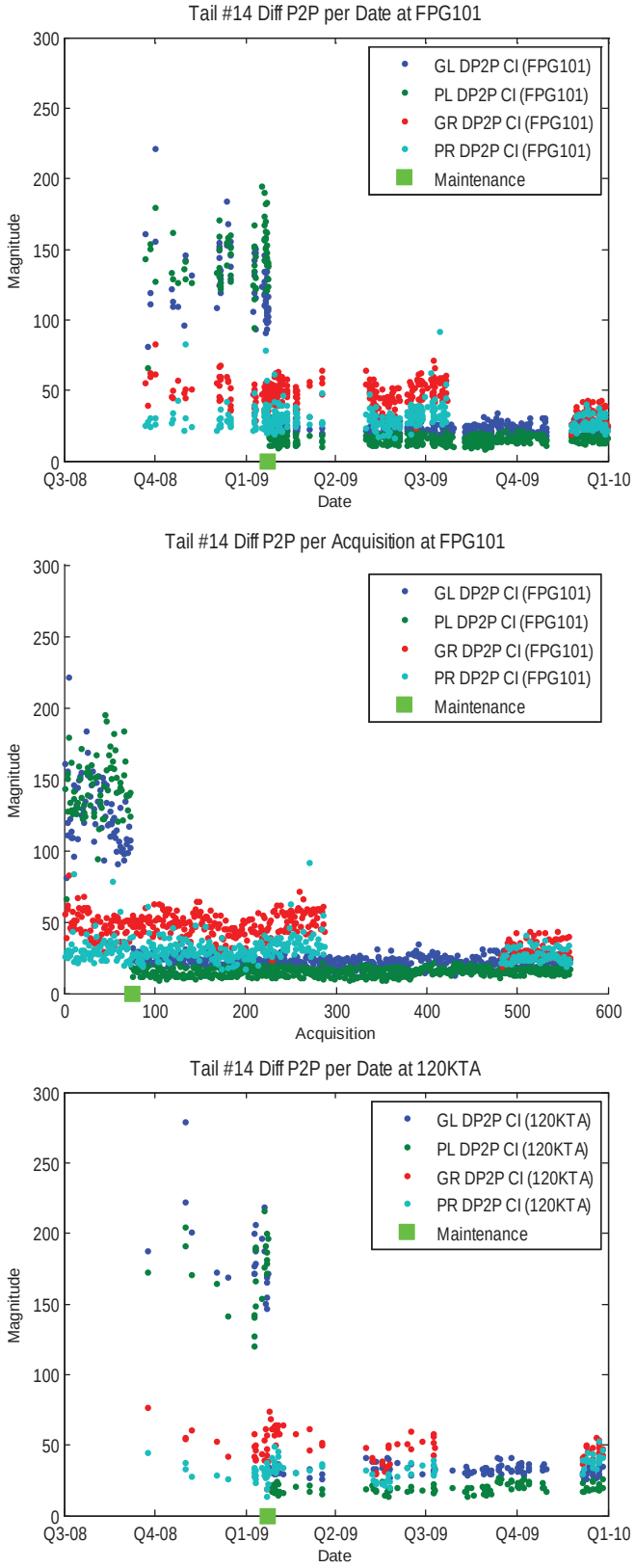

Figure A.14.6.—Tail Number 14 Plots of DP2P per Date, Acquisition and Regime

A.15 Tail Number 15

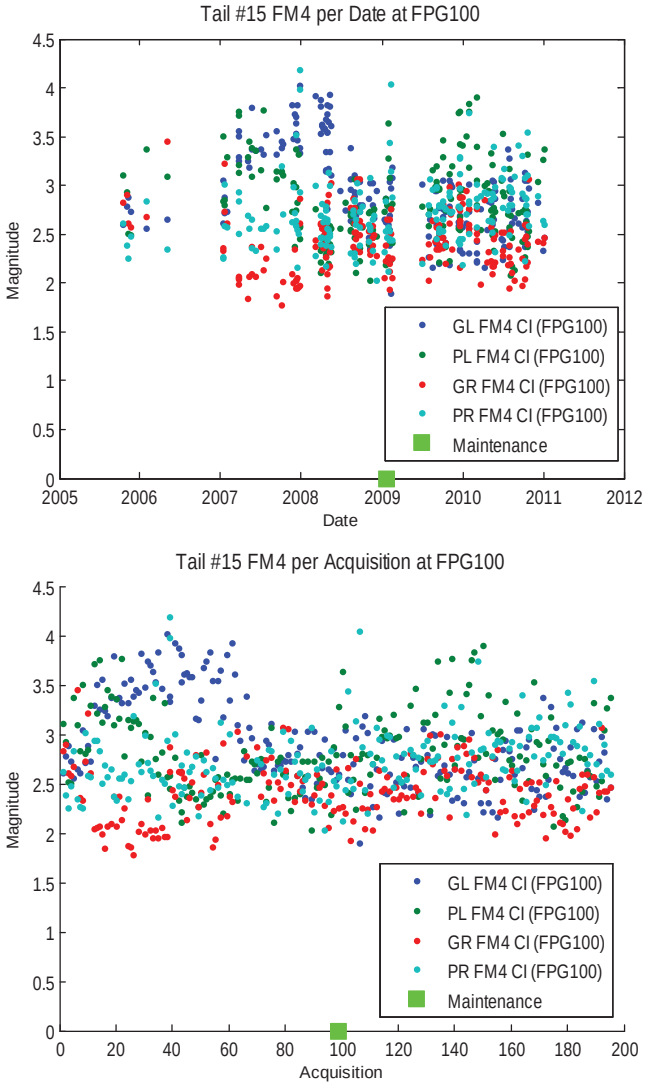

Figure A.15.1.—Tail Number 15 Plots of FM4 per Date and Acquisition

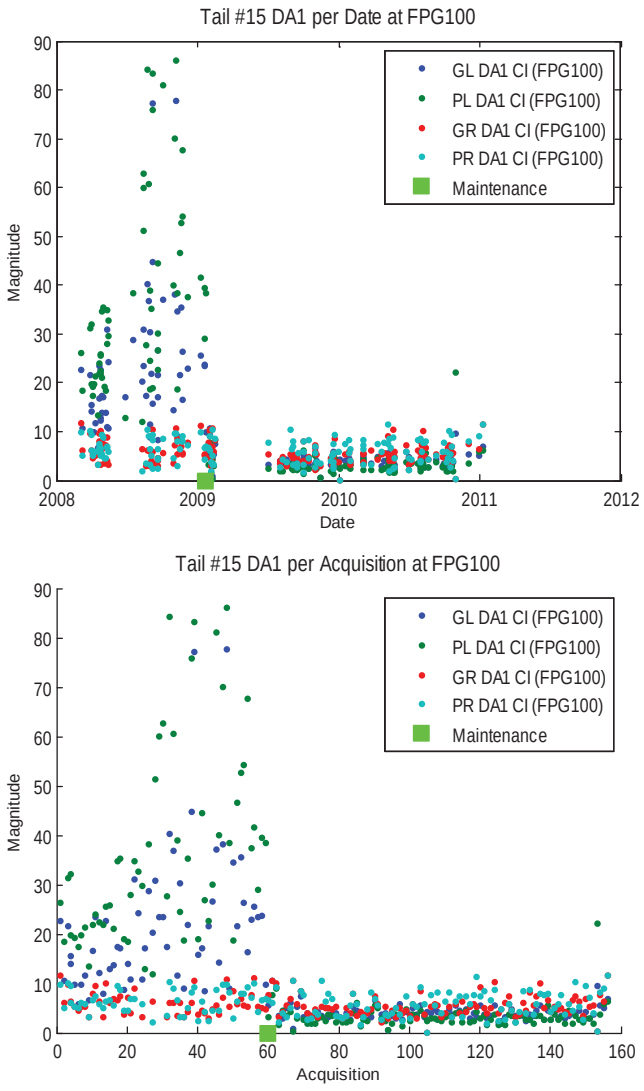

Figure A.15.2.—Tail Number 15 Plots of DA1 per Date and Acquisition

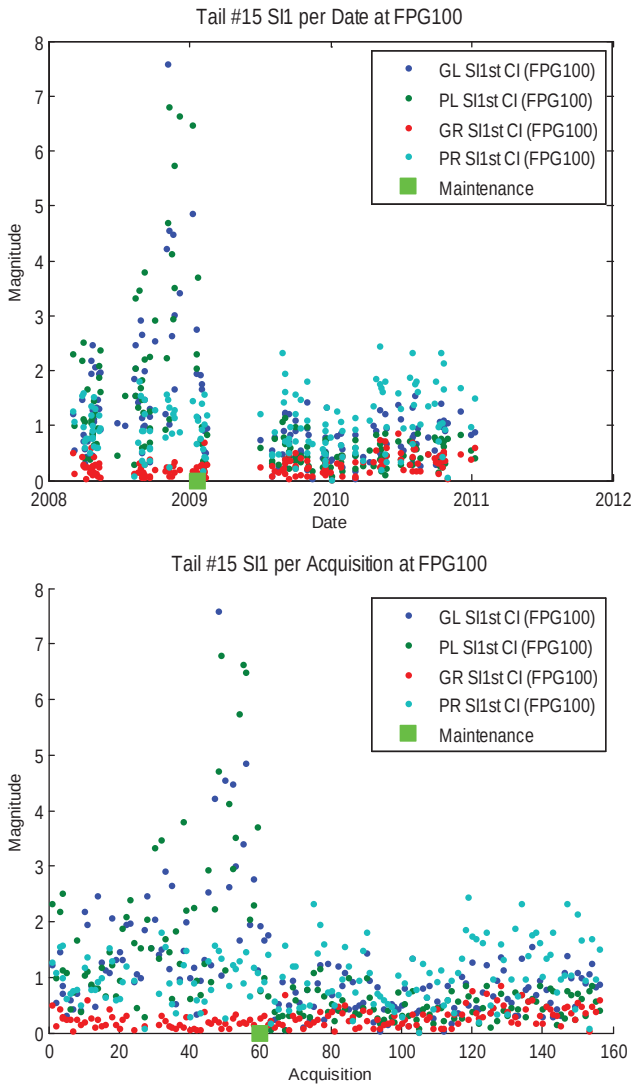

Figure A.15.3.—Tail Number 15 Plots of SI1 per Date and Acquisition

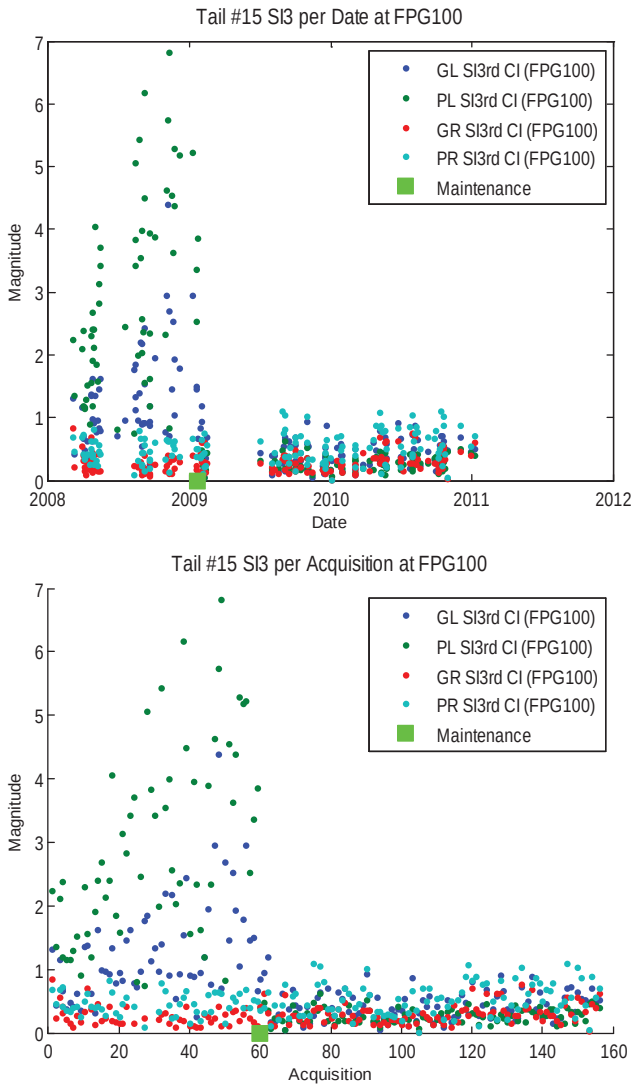

Figure A.15.4.—Tail Number 15 Plots of SI3 per Date and Acquisition

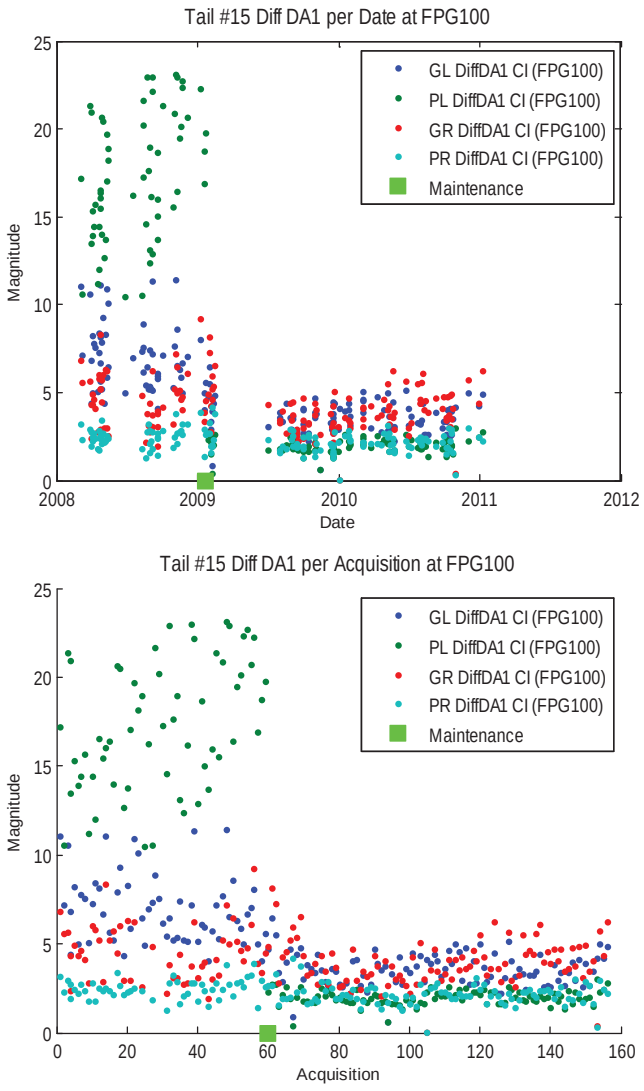

Figure A.15.5.—Tail Number 15 Plots of DiffDA1 per Date and Acquisition

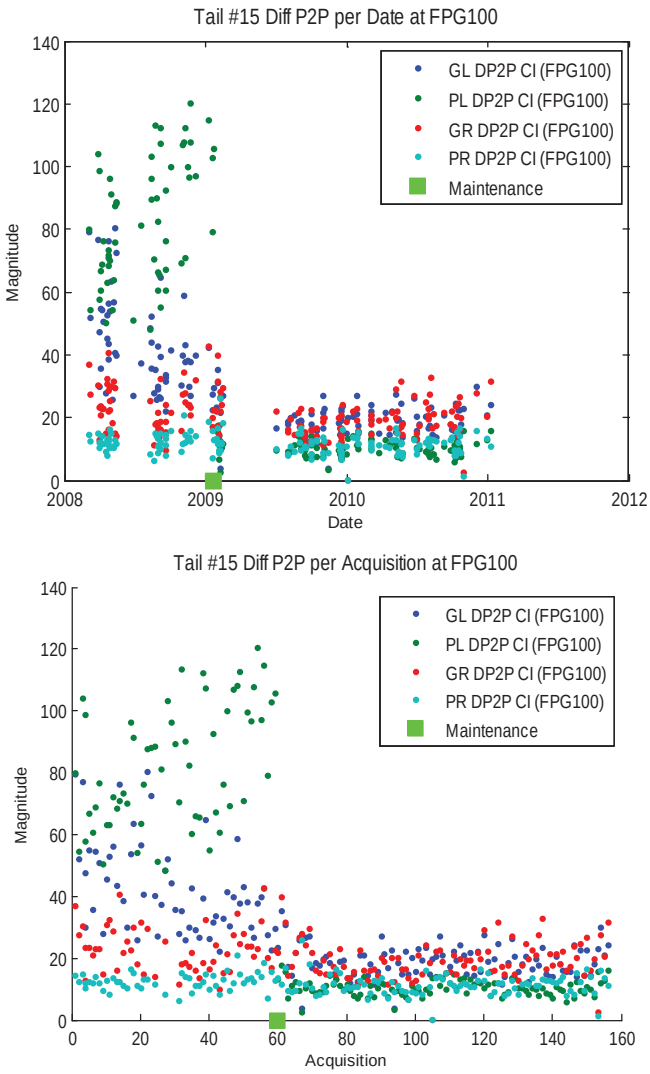

Figure A.15.6.—Tail Number 15 Plots of DP2P per Date and Acquisition

A.16 Tail Number 16

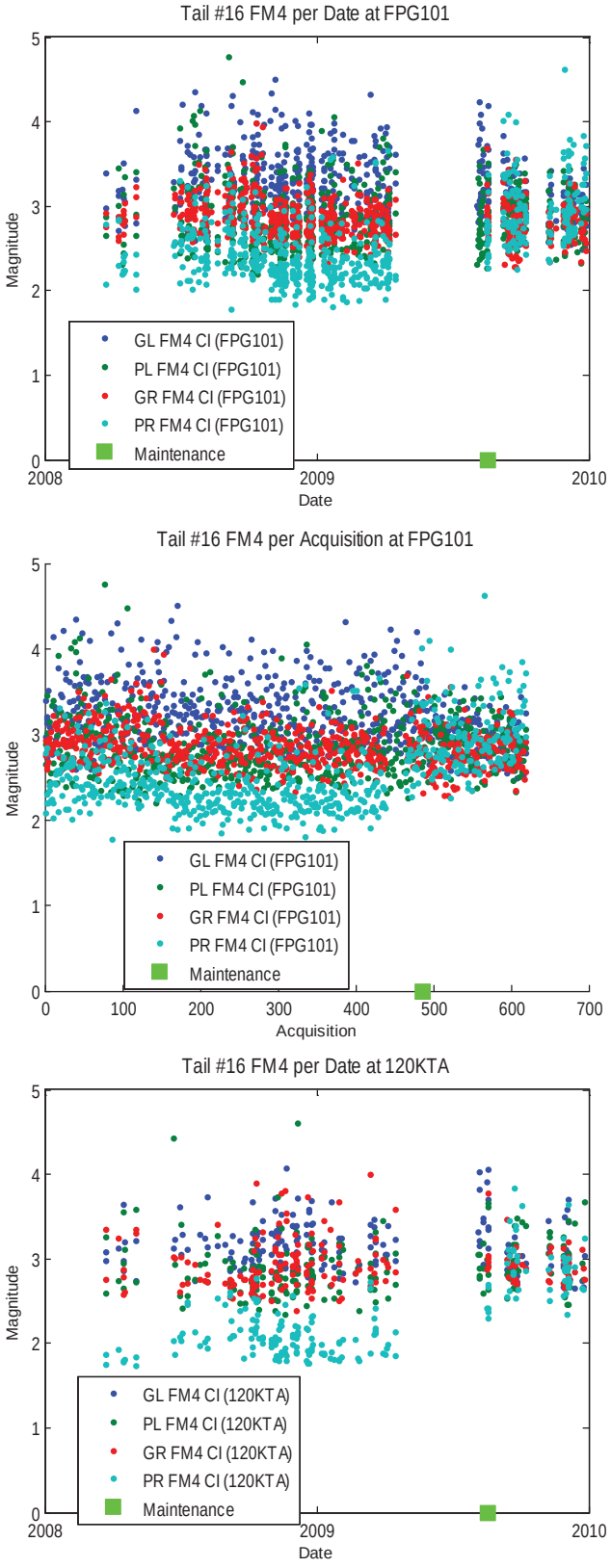

Figure A.16.1.—Tail Number 16 Plots of FM4 per Date, Acquisition and Regime

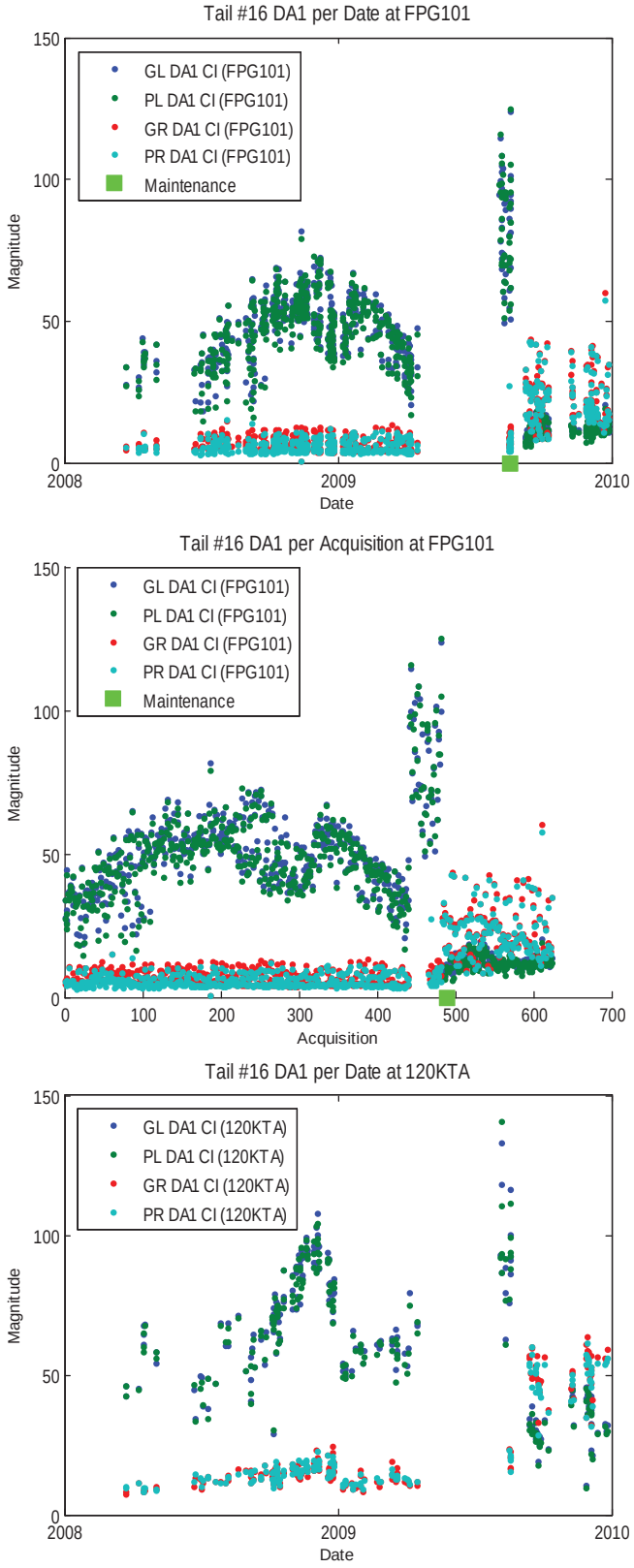

Figure A.16.2.—Tail Number 16 Plots of DA1 per Date, Acquisition and Regime

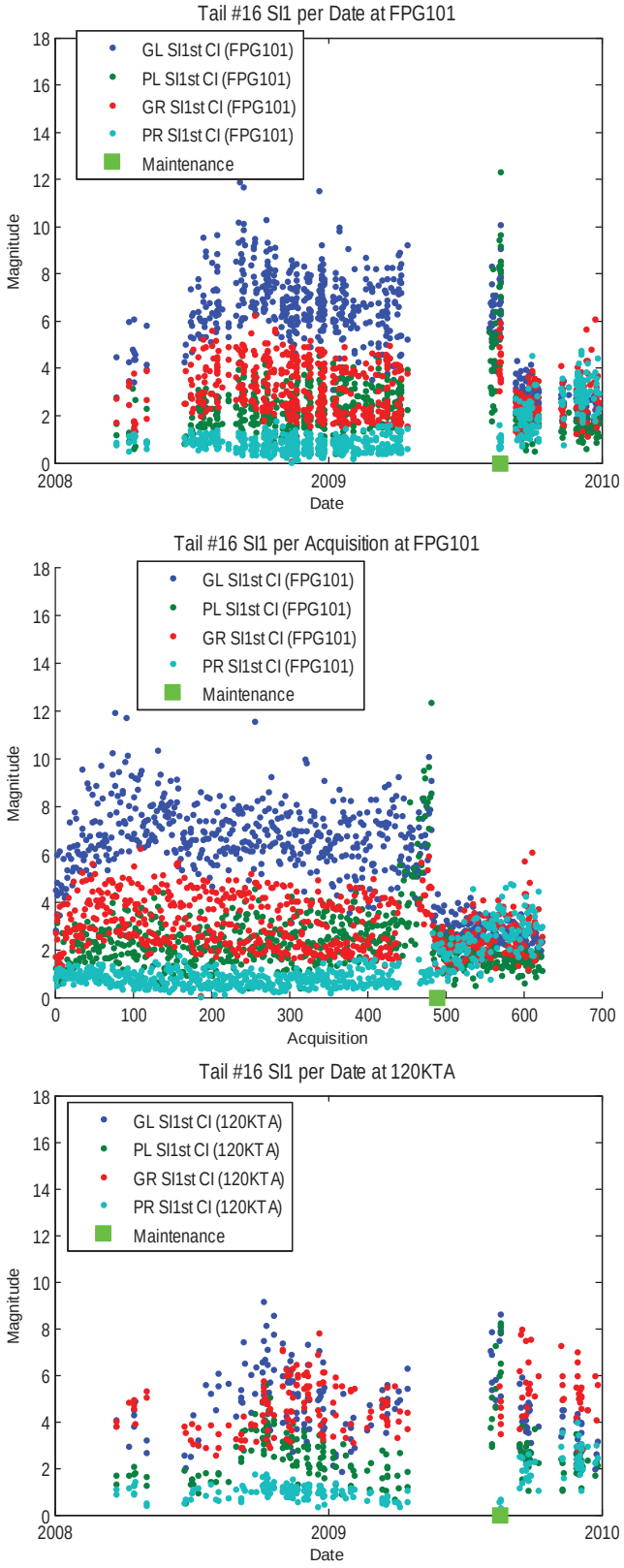

Figure A.16.3.—Tail Number 16 Plots of SI1 per Date, Acquisition and Regime

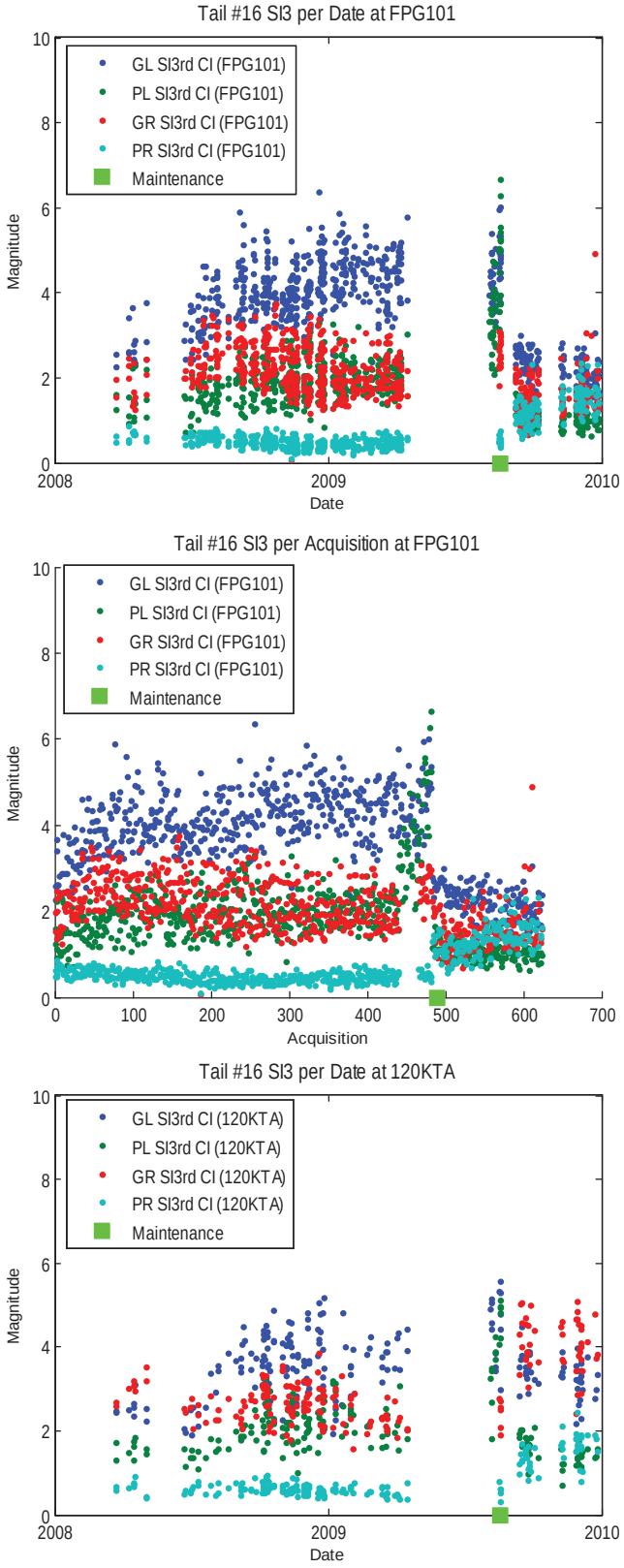

Figure A.16.4.—Tail Number 16 Plots of SI3 per Date, Acquisition and Regime

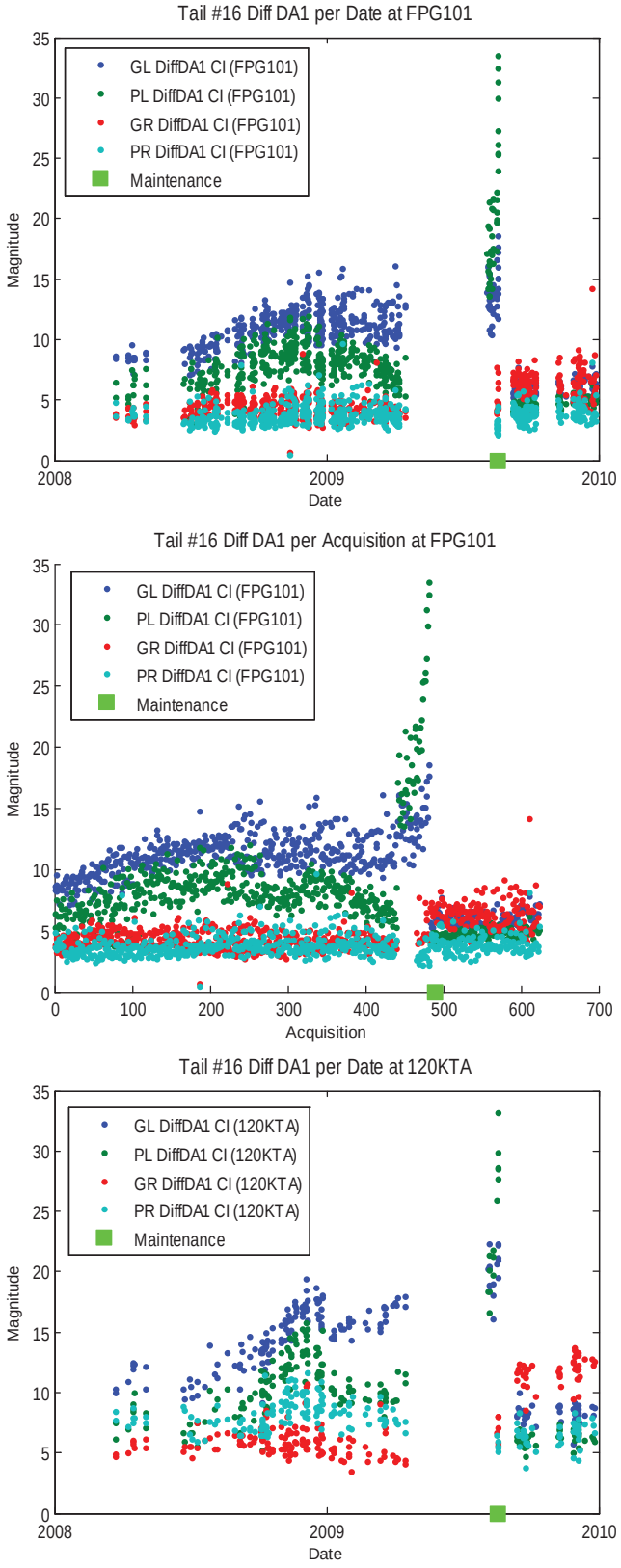

Figure A.16.5.—Tail Number 16 Plots of DiffDA1 per Date, Acquisition and Regime

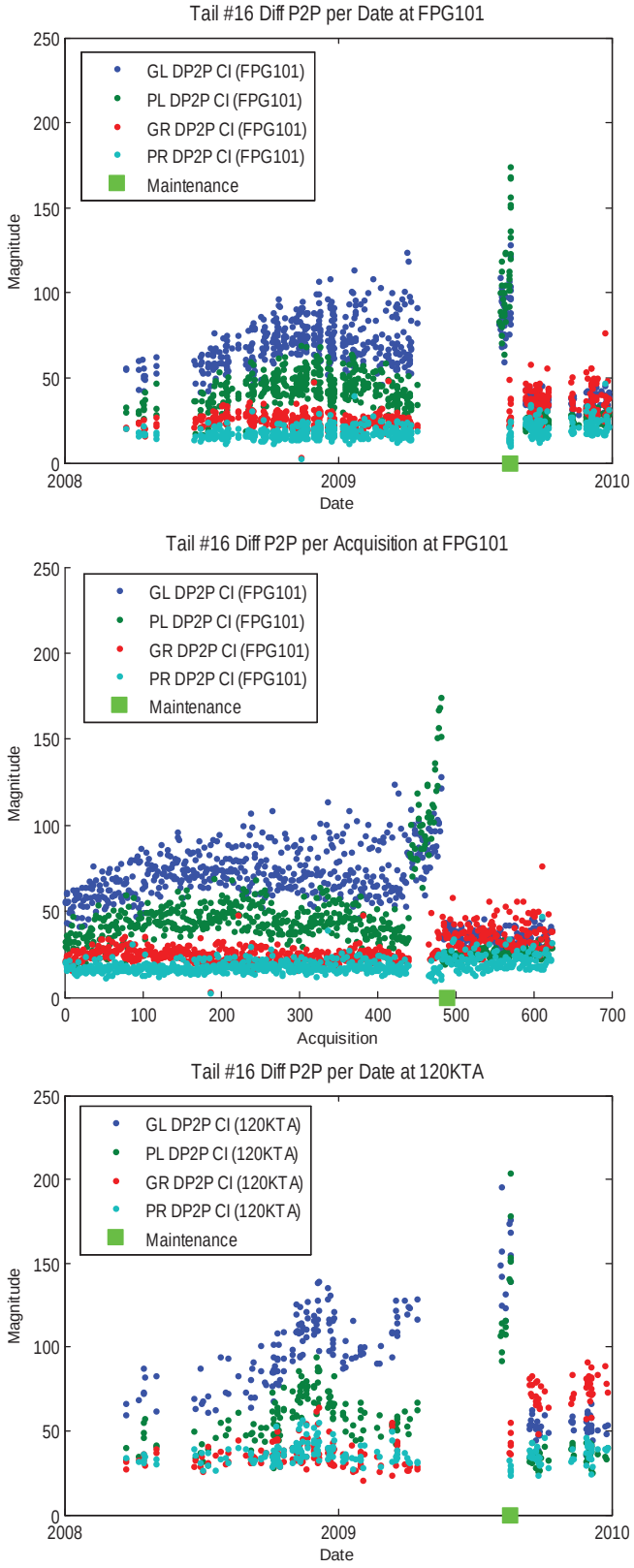

Figure A.16.6.—Tail Number 16 Plots of DP2P per Date, Acquisition and Regime

A.17 Tail Number 17

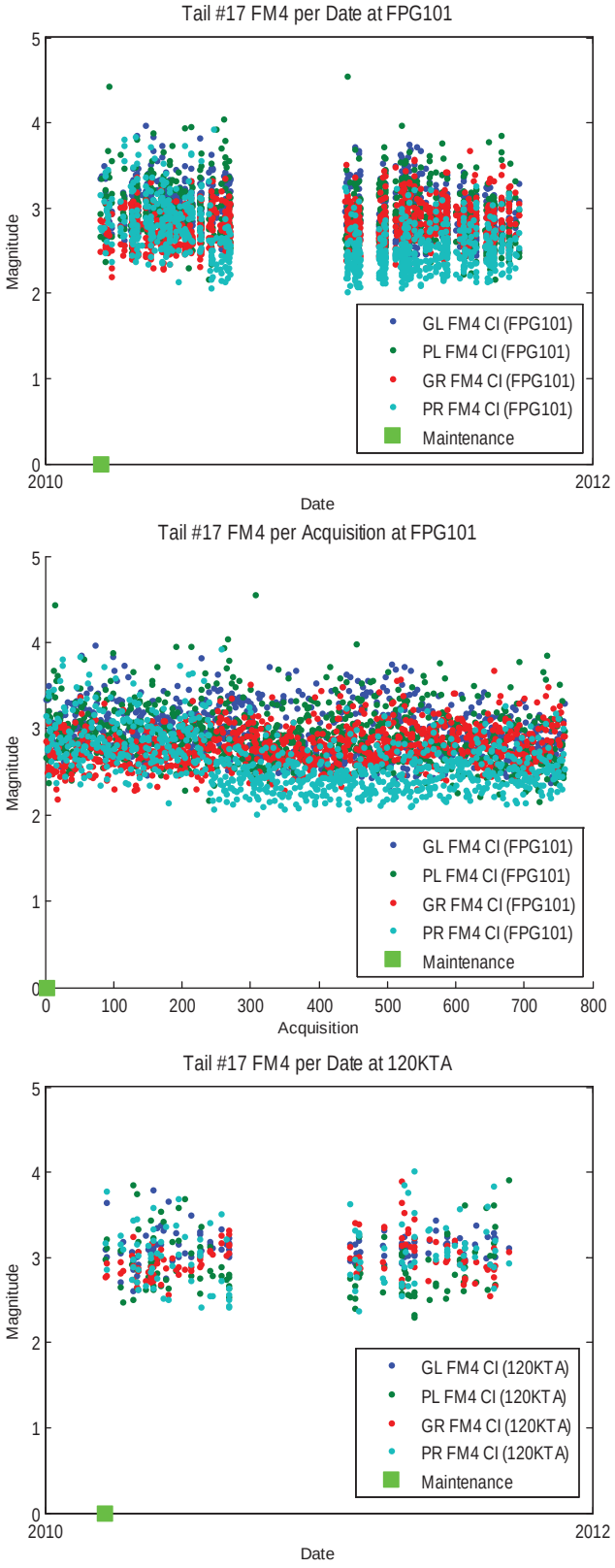

Figure A.17.1.—Tail Number 17 Plots of FM4 per Date, Acquisition and Regime

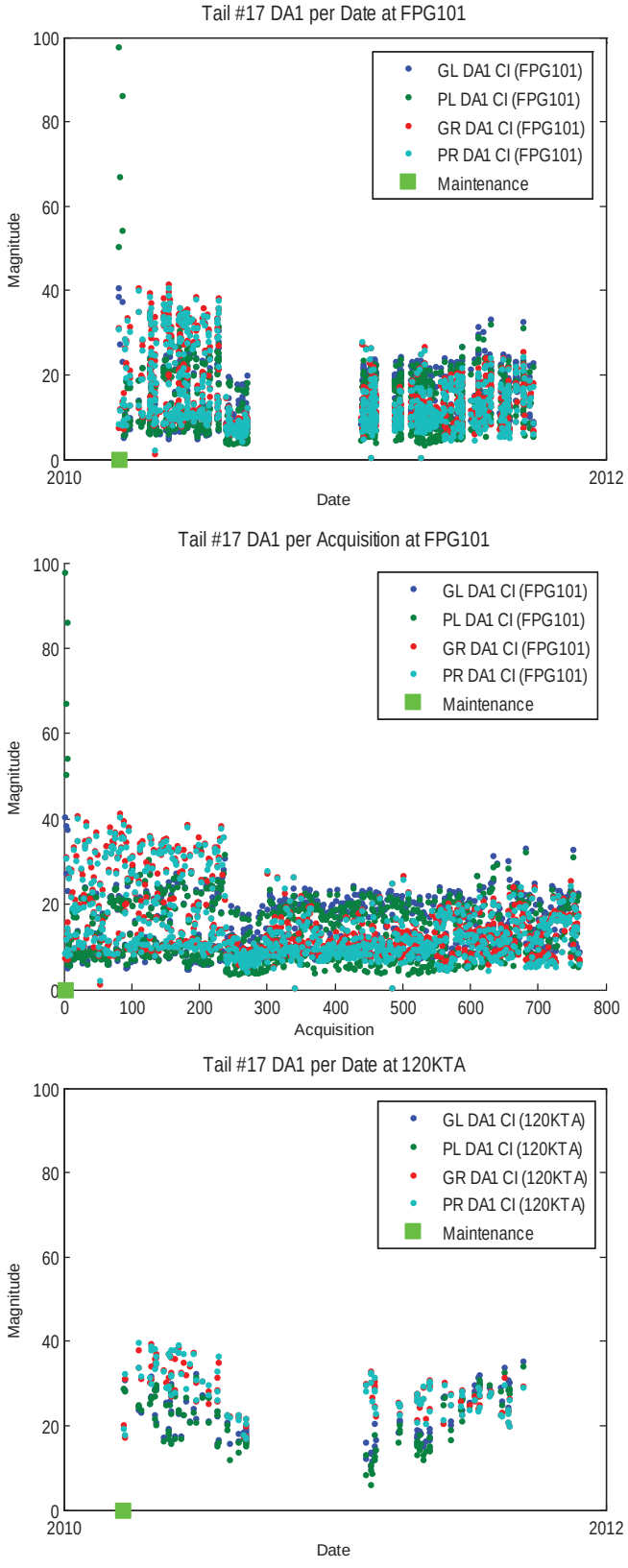

Figure A.17.2.—Tail Number 17 Plots of DA1 per Date, Acquisition and Regime

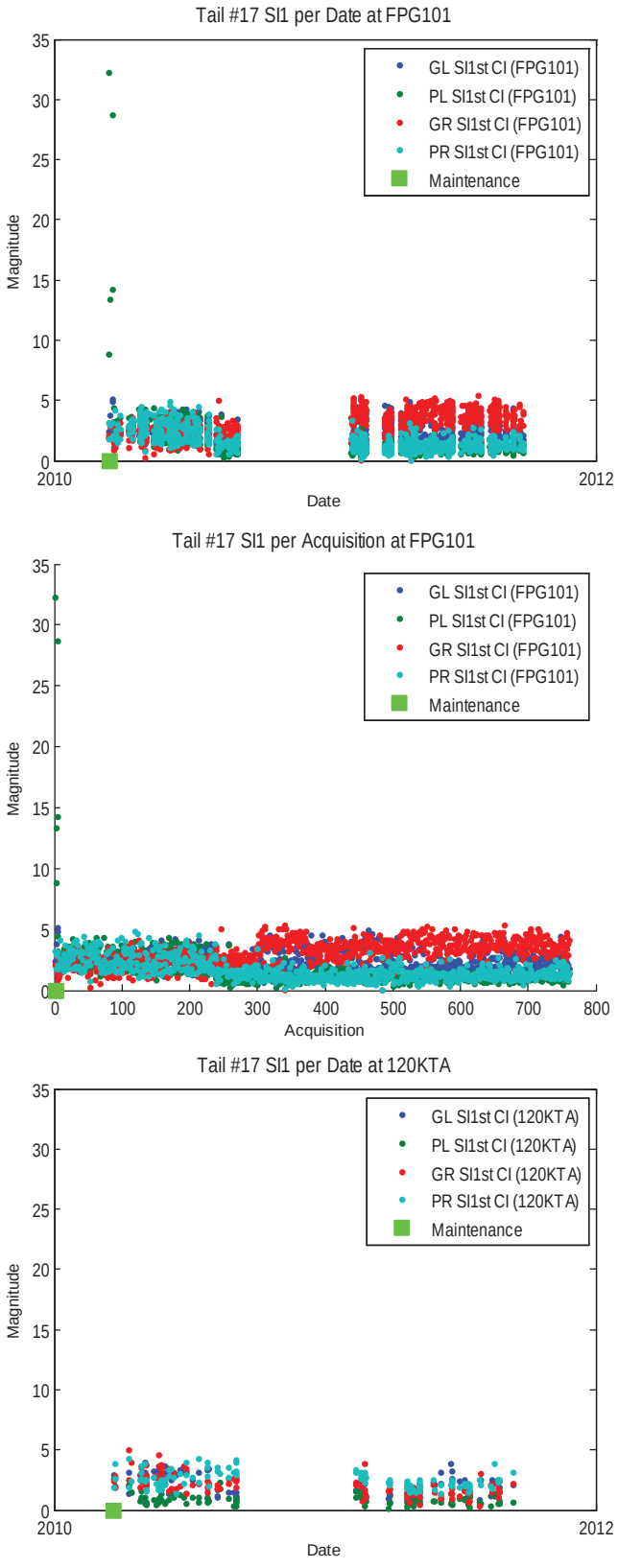

Figure A.17.3.—Tail Number 17 Plots of SI1 per Date, Acquisition and Regime

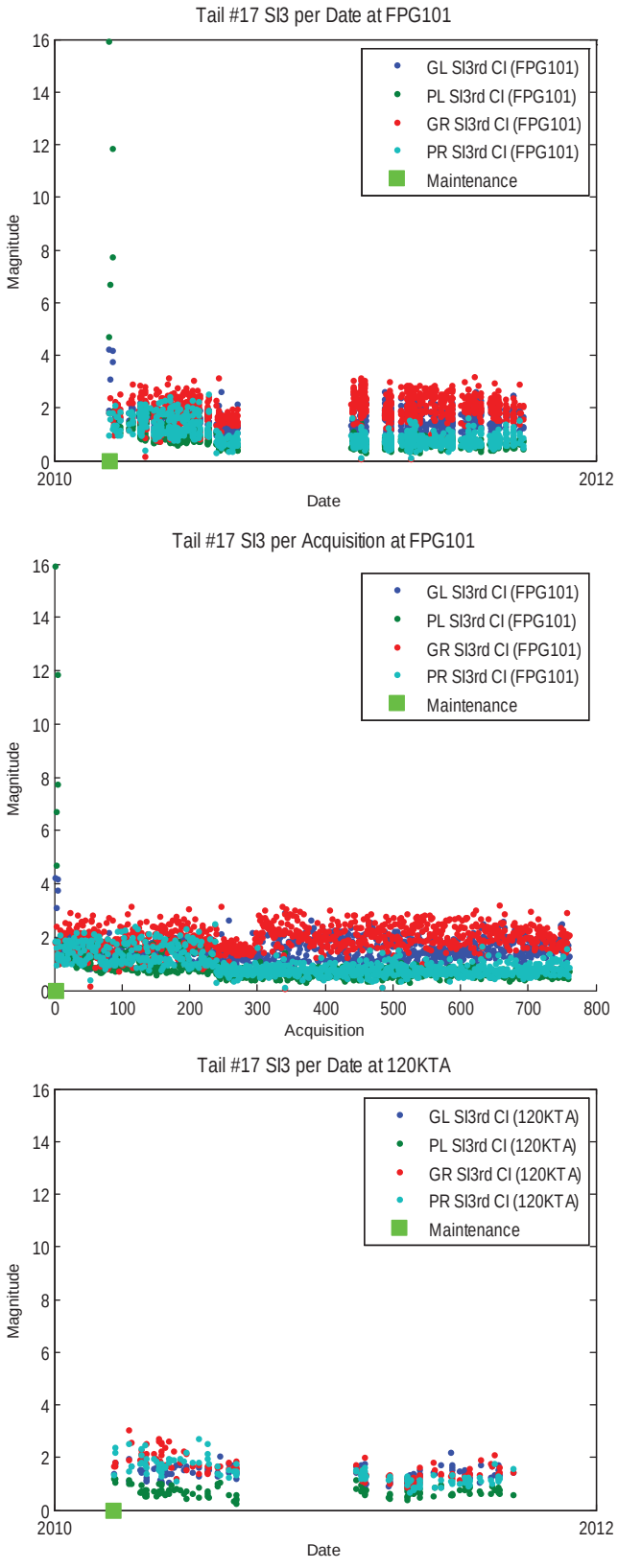

Figure A.17.4.—Tail Number 17 Plots of SI3 per Date, Acquisition and Regime

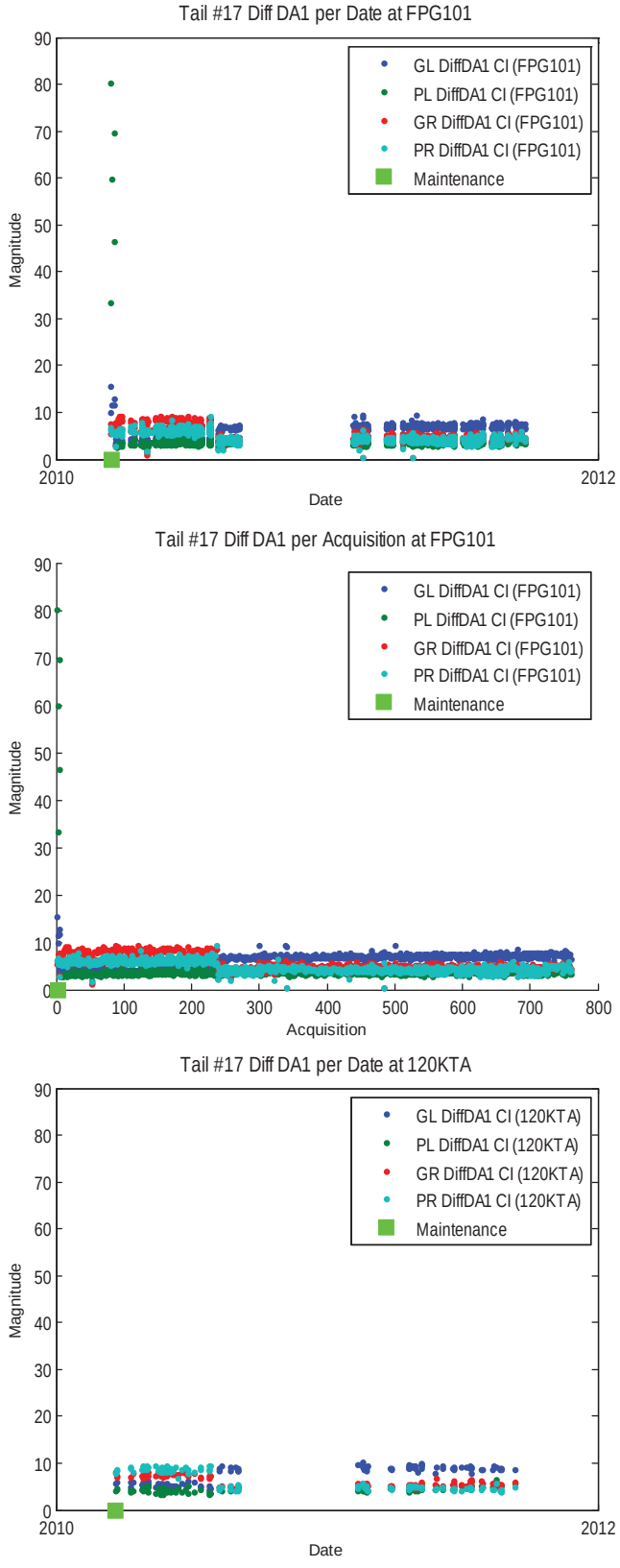

Figure A.17.5.—Tail Number 17 Plots of DiffDA1 per Date, Acquisition and Regime

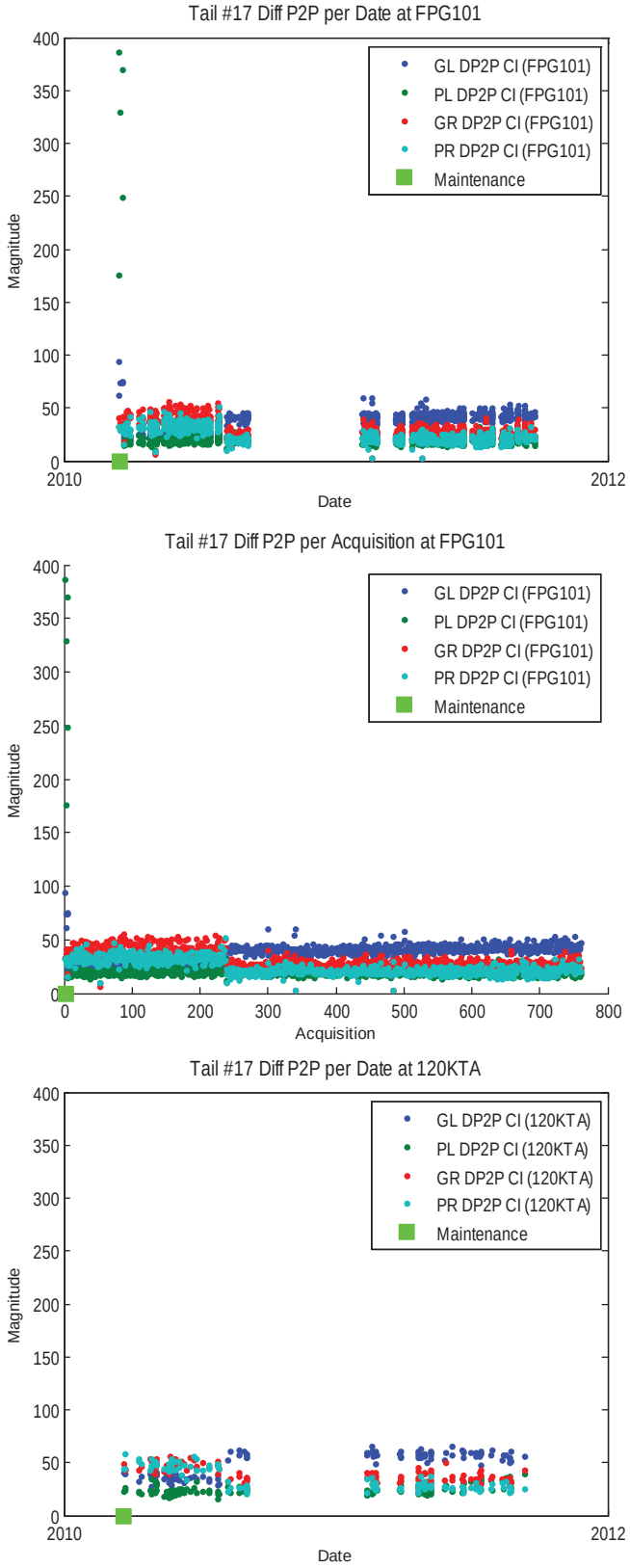

Figure A.17.6.—Tail Number 17 Plots of DP2P per Date, Acquisition and Regime

A.18 Tail Number 18

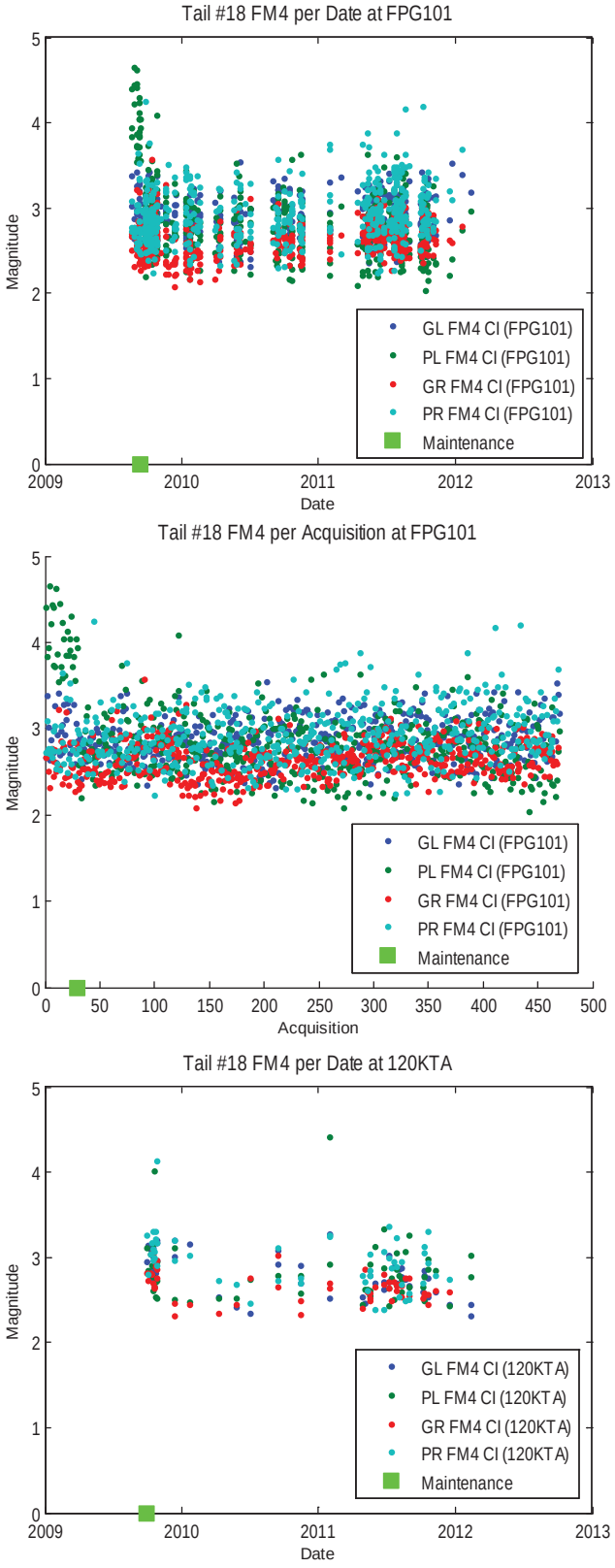

Figure A.18.1.—Tail Number 18 Plots of FM4 per Date, Acquisition and Regime

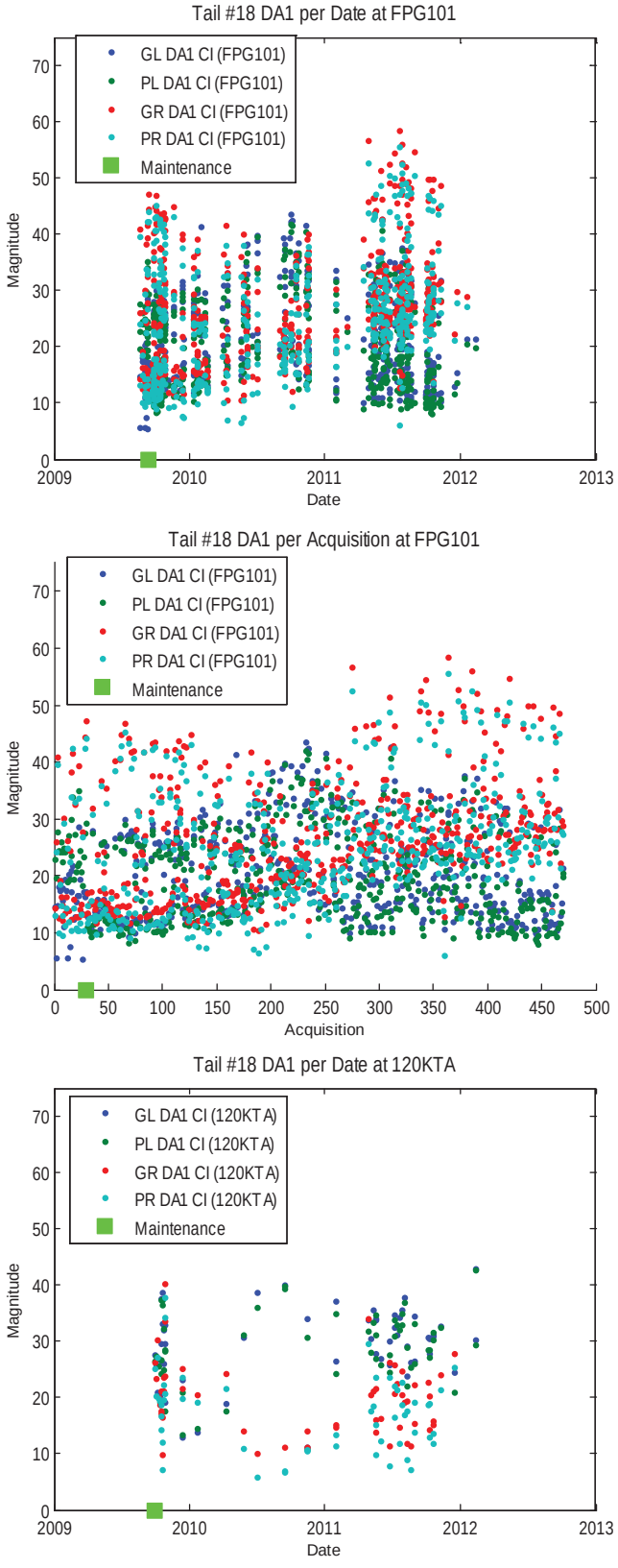

Figure A.18.2.—Tail Number 18 Plots of DA1 per Date, Acquisition and Regime

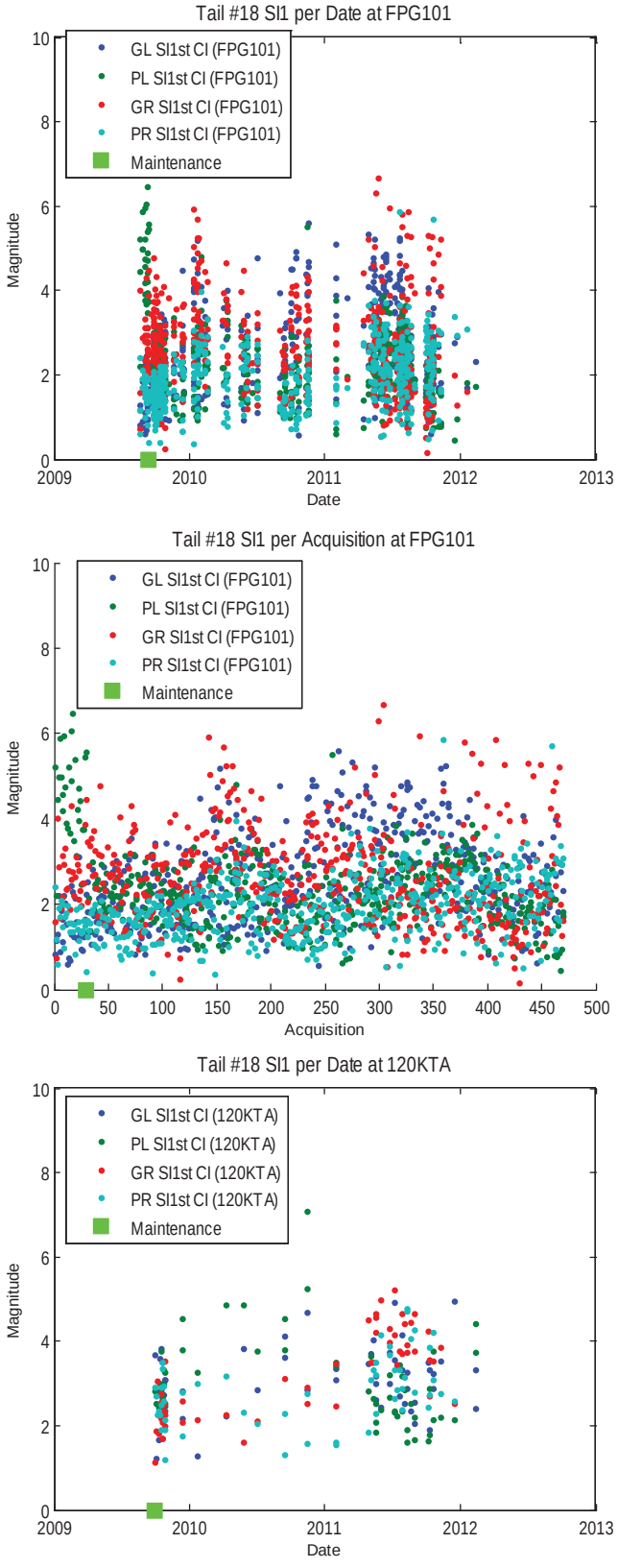

Figure A.18.3.—Tail Number 18 Plots of SI1 per Date, Acquisition and Regime

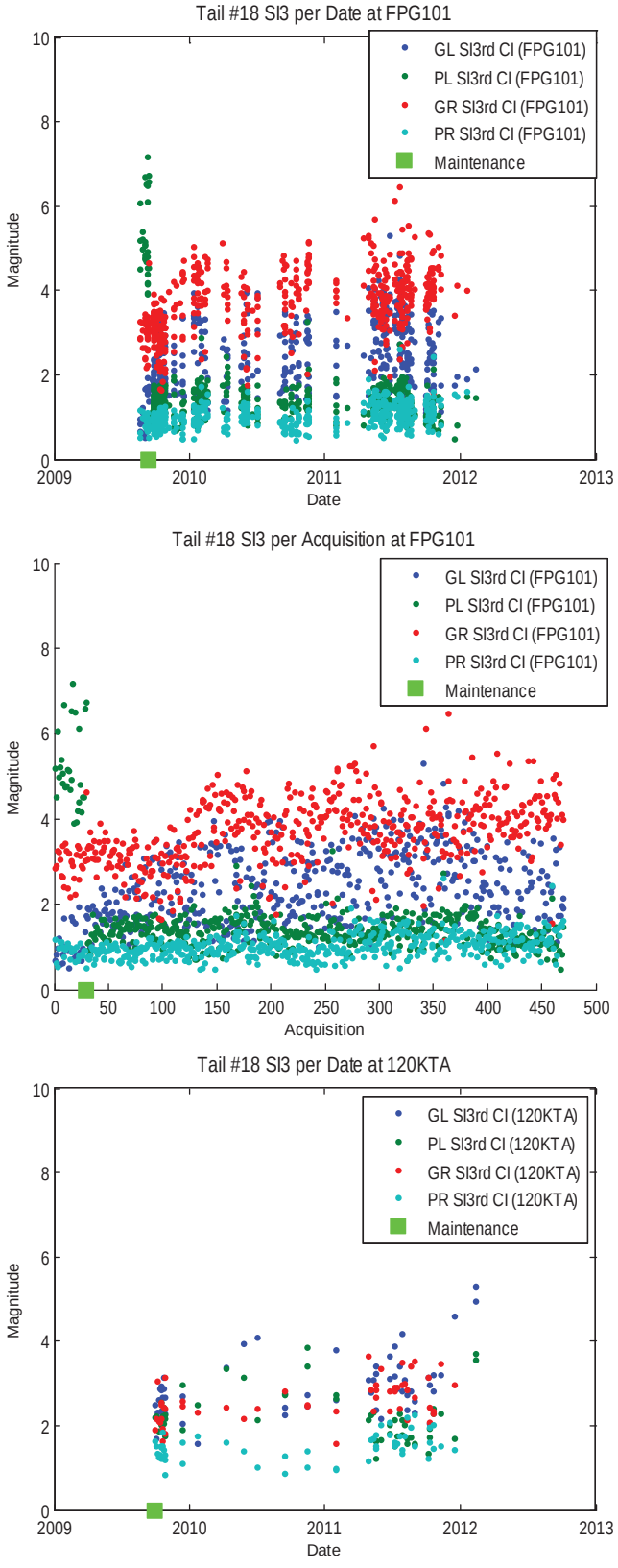

Figure A.18.4.—Tail Number 18 Plots of SI3 per Date, Acquisition and Regime

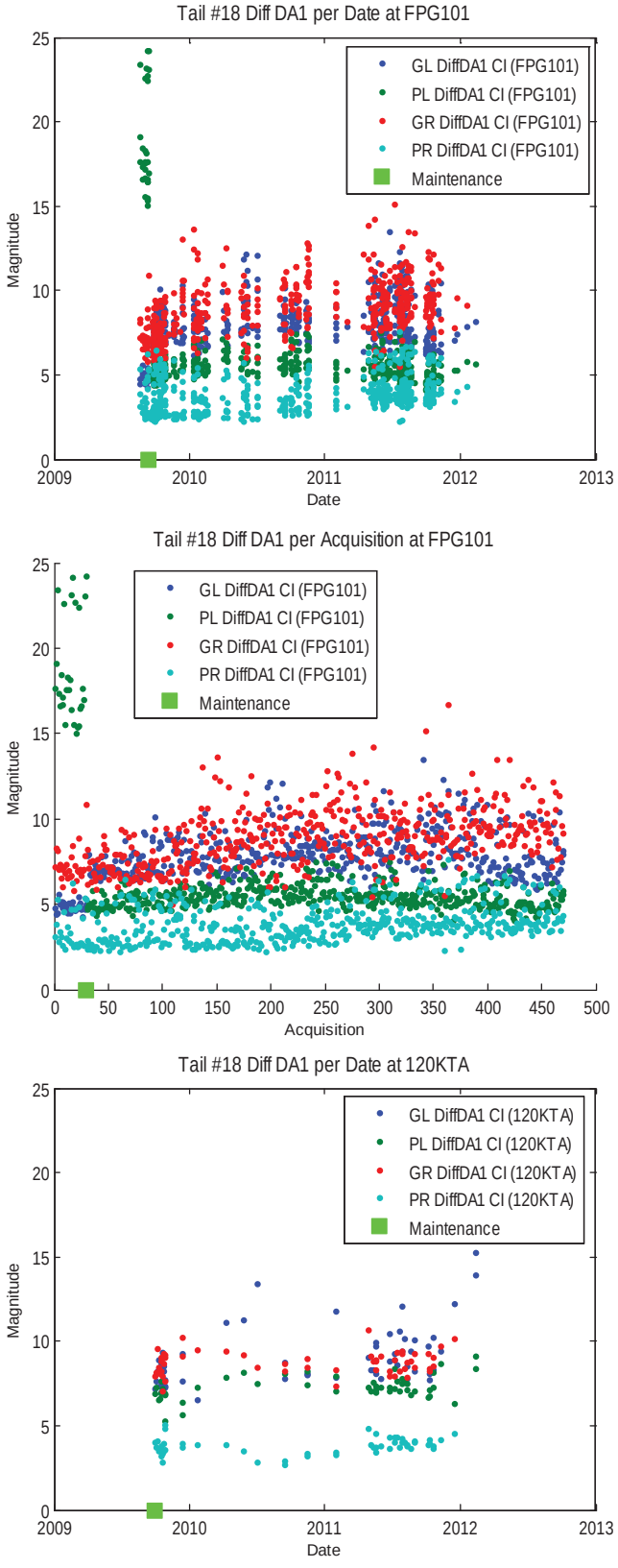

Figure A.18.5.—Tail Number 18 Plots of DiffDA1 per Date, Acquisition and Regime

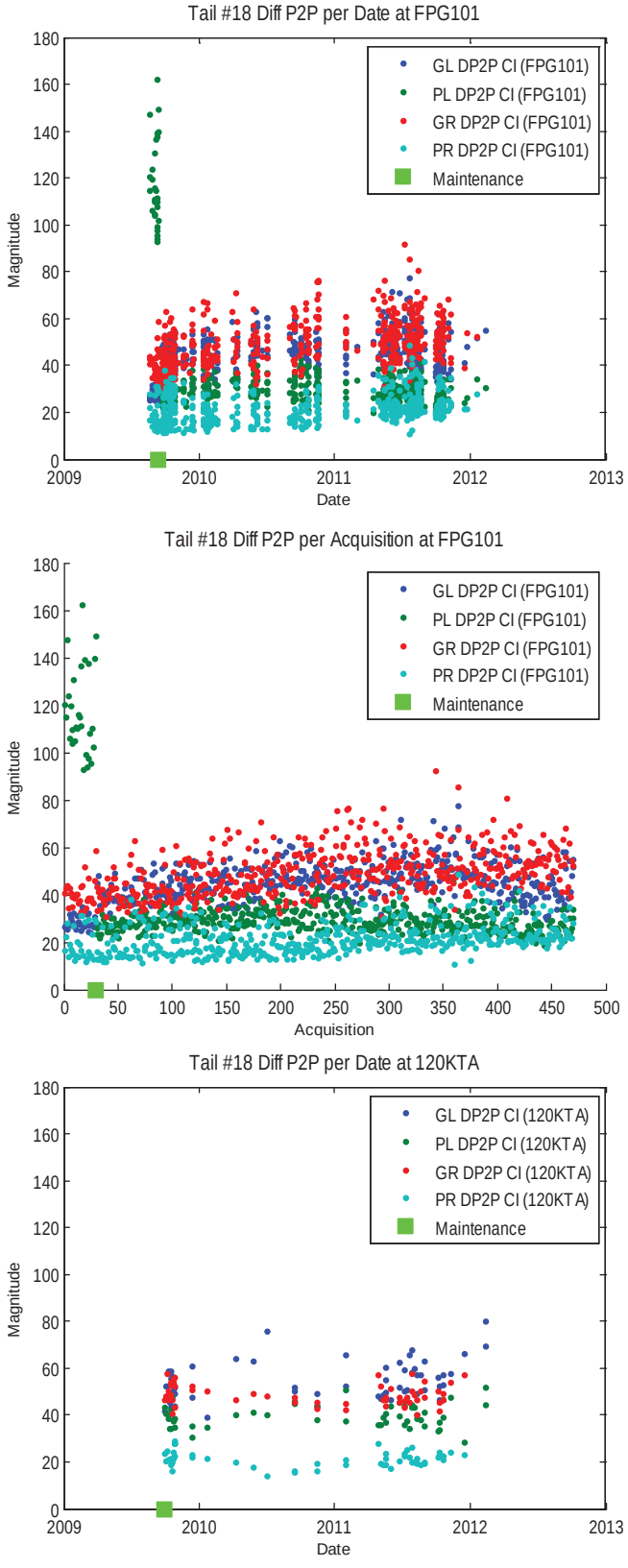

Figure A.18.6.—Tail Number 18 Plots of DP2P per Date, Acquisition and Regime

A.19 Tail Number 19

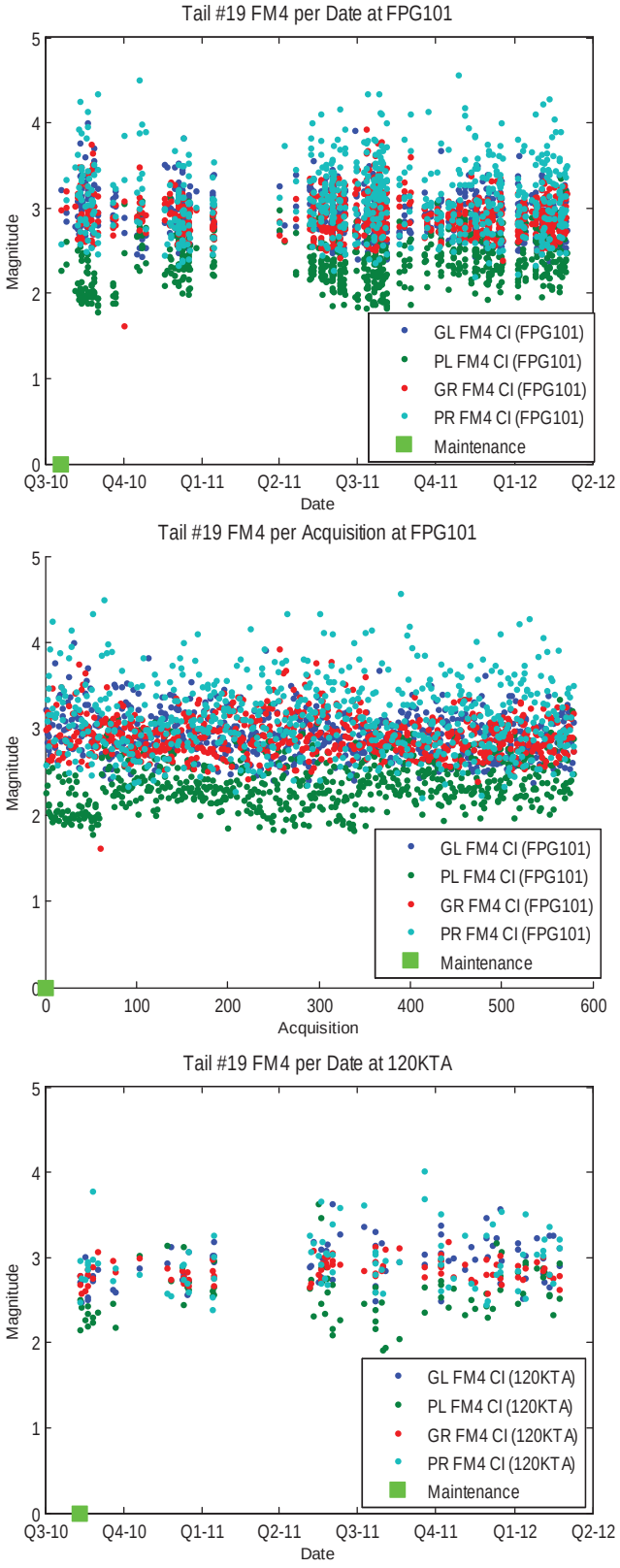

Figure A.19.1.—Tail Number 19 Plots of FM4 per Date, Acquisition and Regime

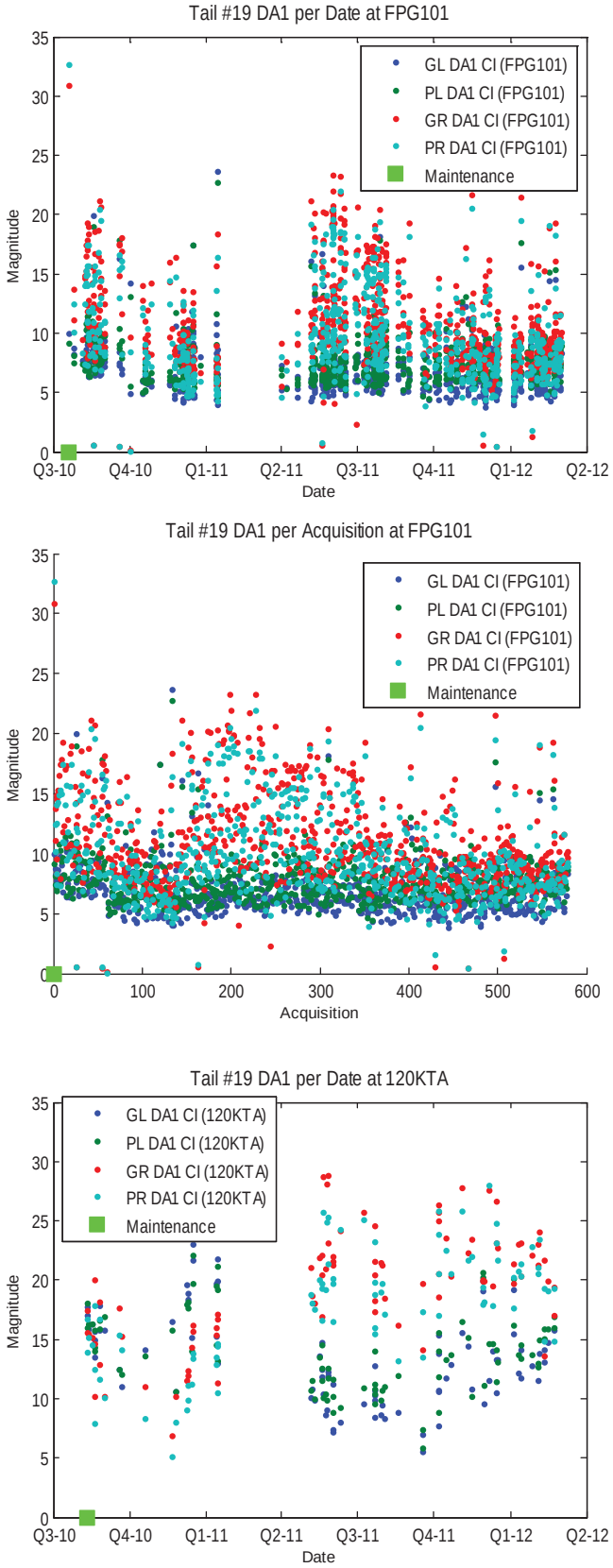

Figure A.19.2.—Tail Number 19 Plots of DA1 per Date, Acquisition and Regime

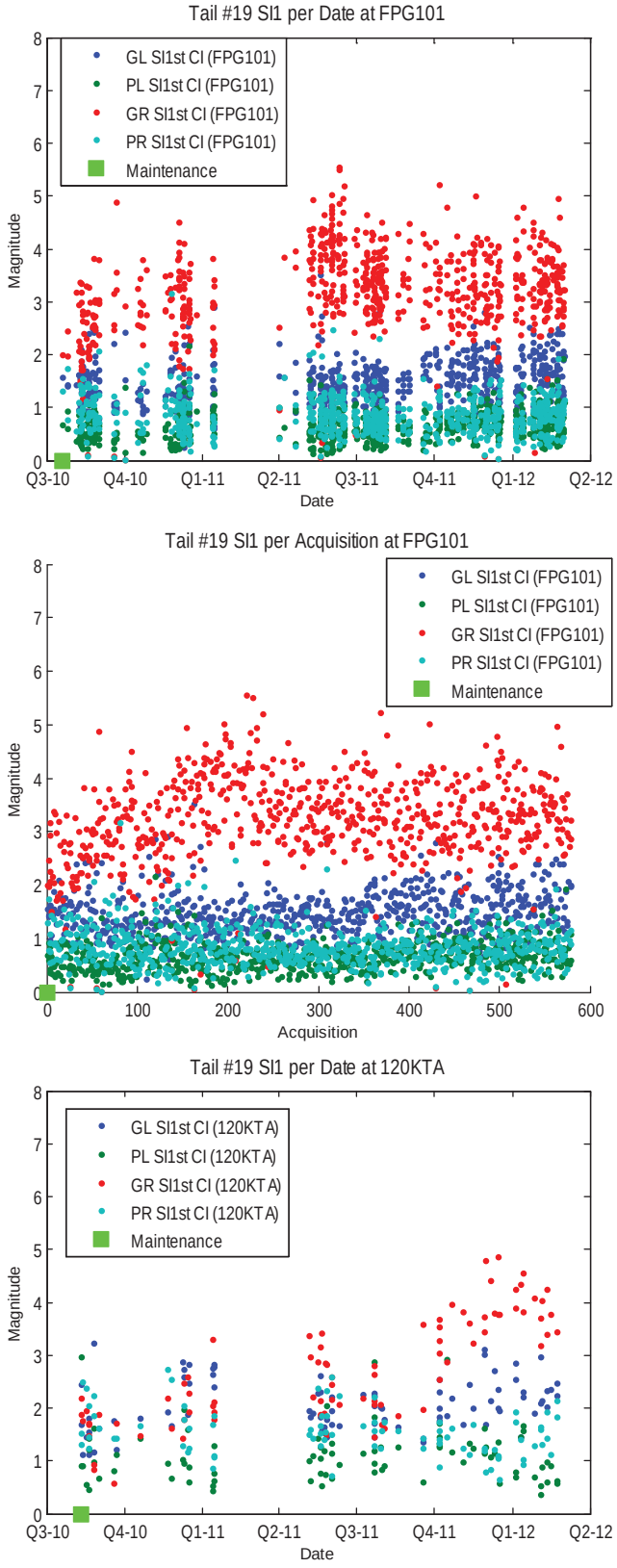

Figure A.19.3.—Tail Number 19 Plots of SI1 per Date, Acquisition and Regime

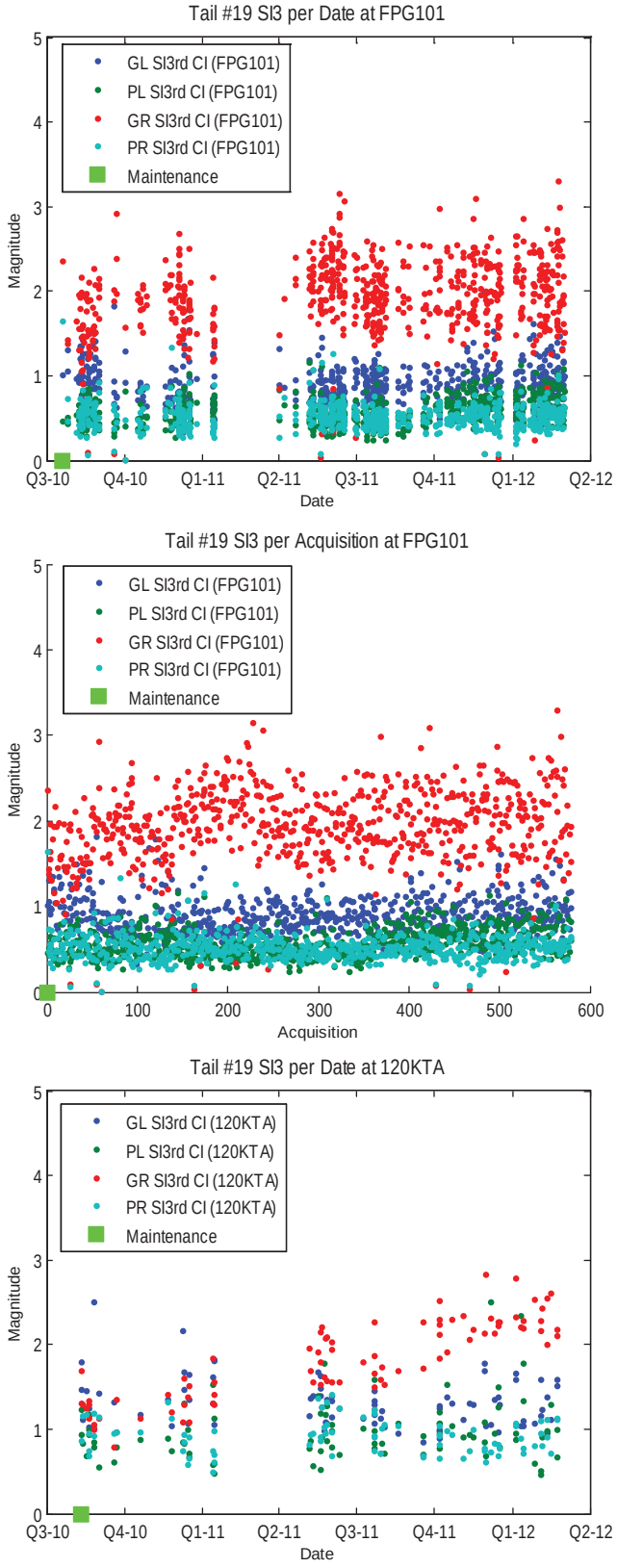

Figure A.19.4.—Tail Number 19 Plots of SI3 per Date, Acquisition and Regime

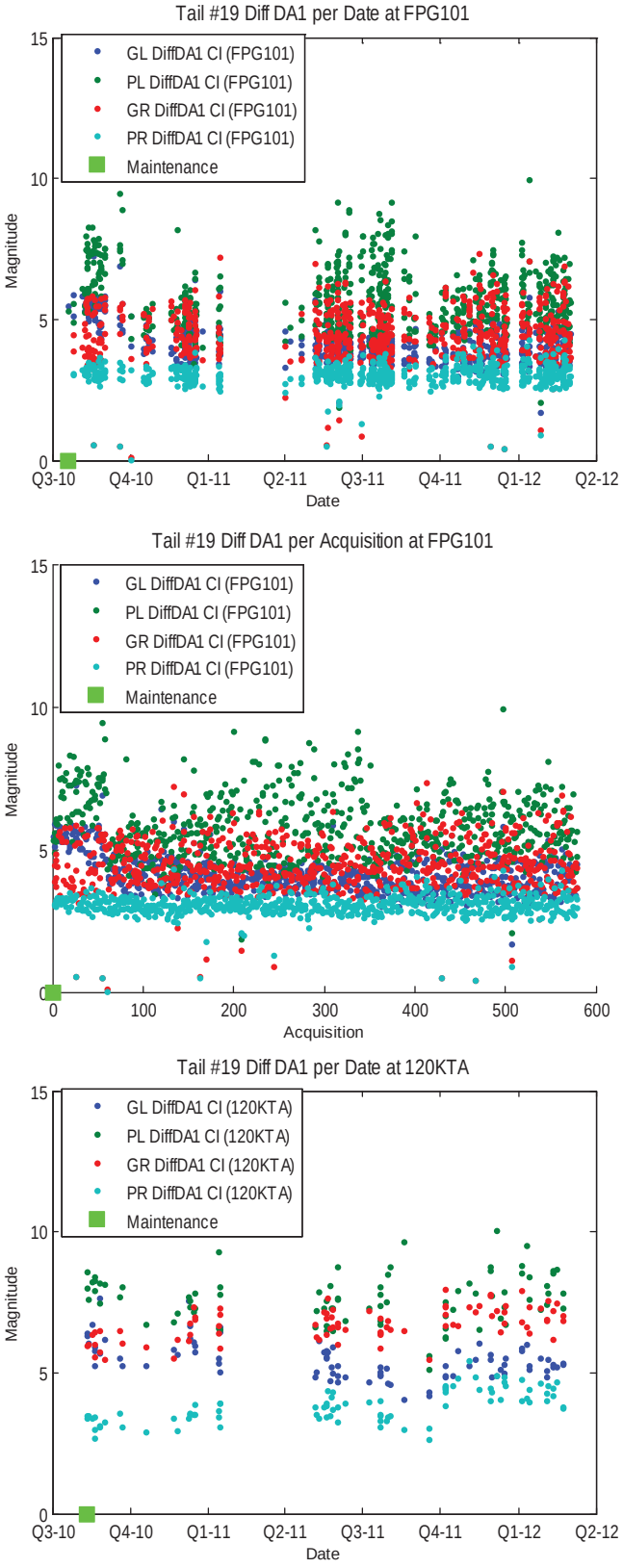

Figure A.19.5.—Tail Number 19 Plots of DiffDA1 per Date, Acquisition and Regime

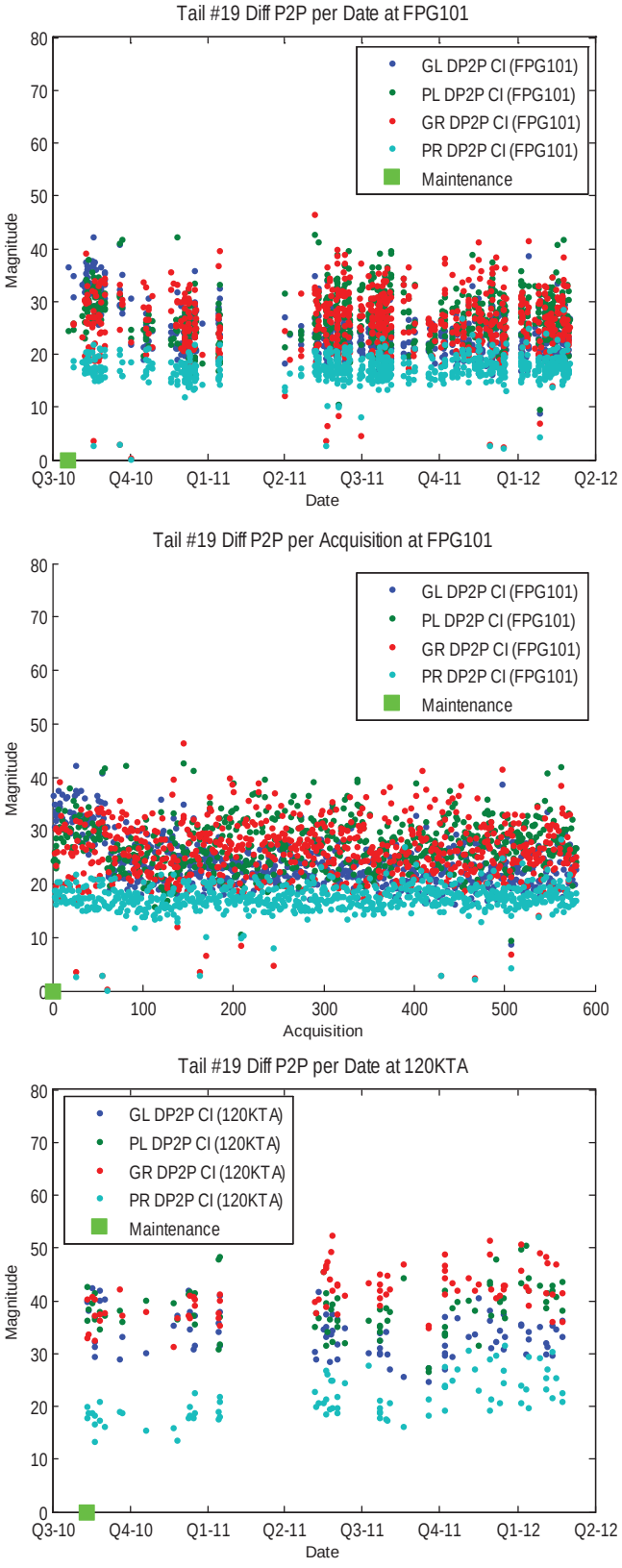

Figure A.19.6.—Tail Number 19 Plots of DP2P per Date, Acquisition and Regime

A.20 Tail Number 20

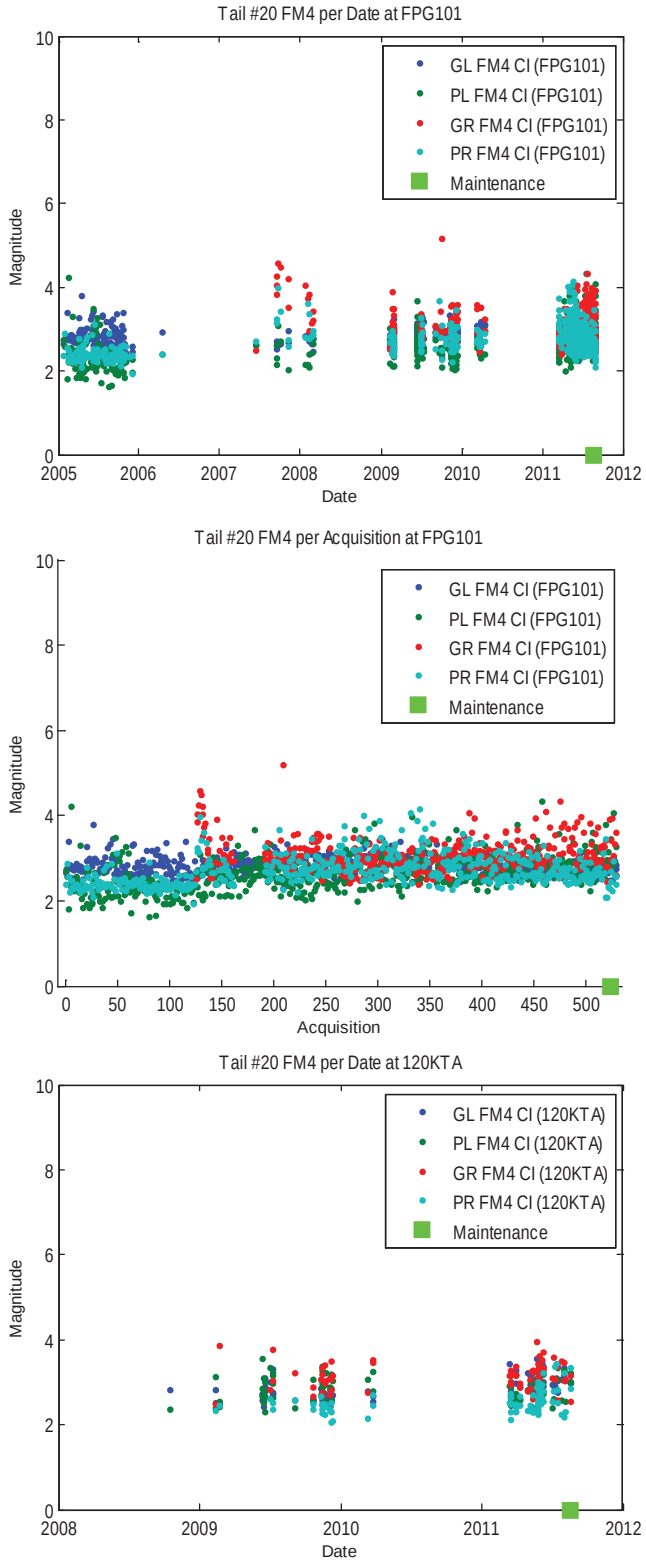

Figure A.20.1.—Tail Number 20 Plots of FM4 per Date, Acquisition and Regime

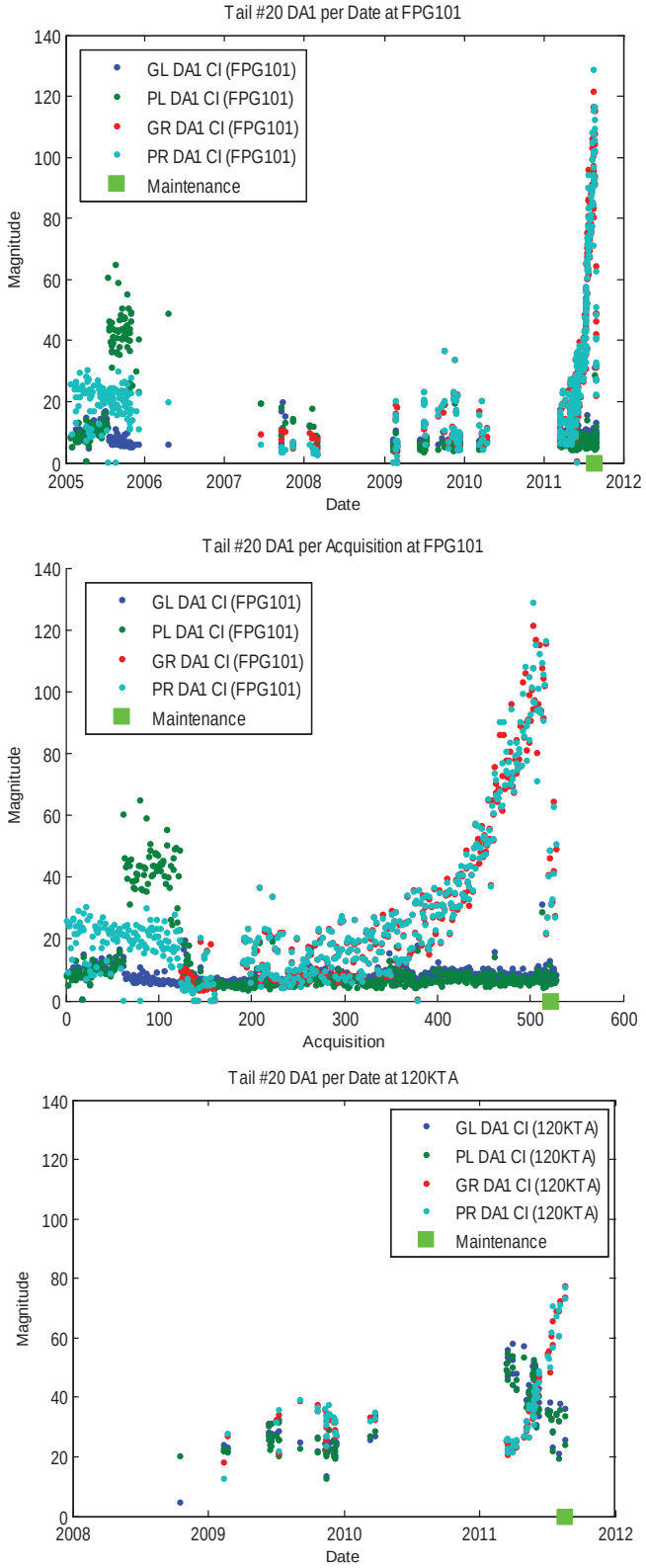

Figure A.20.2.—Tail Number 20 Plots of DA1 per Date, Acquisition and Regime

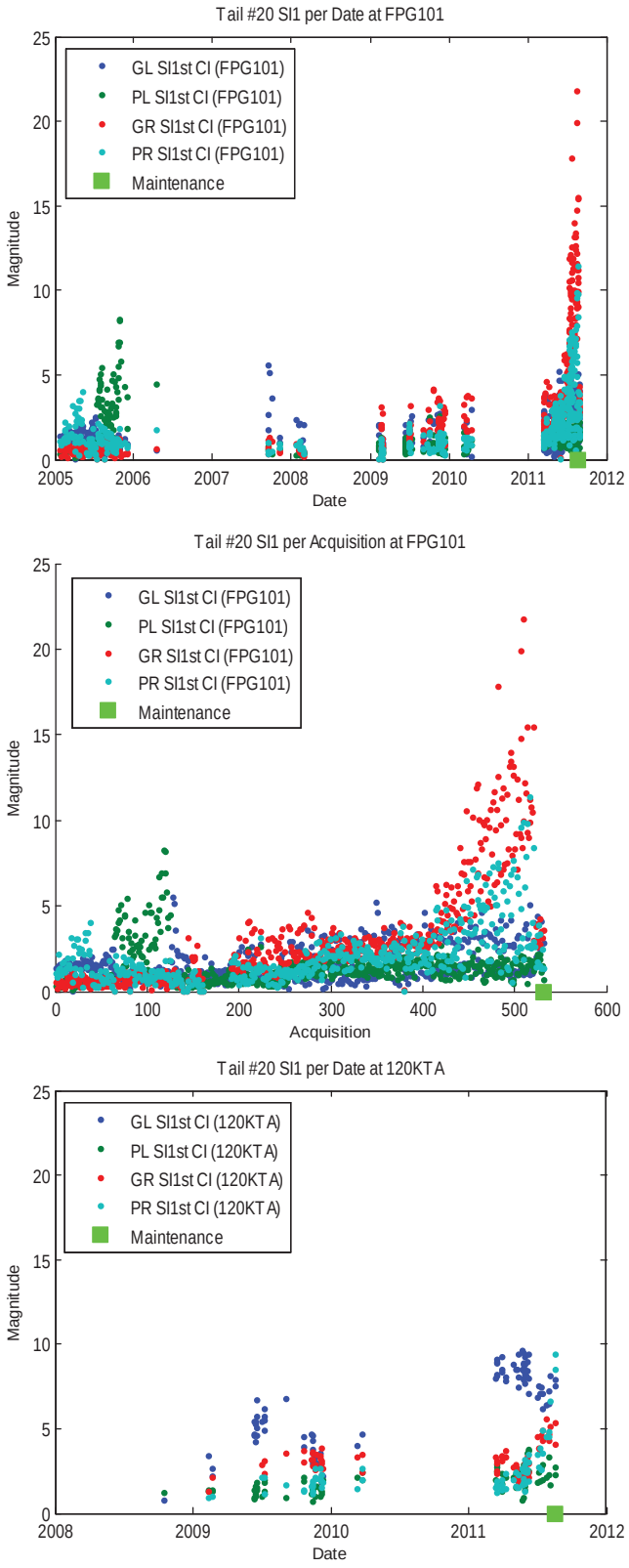

Figure A.20.3.—Tail Number 20 Plots of SI1 per Date, Acquisition and Regime

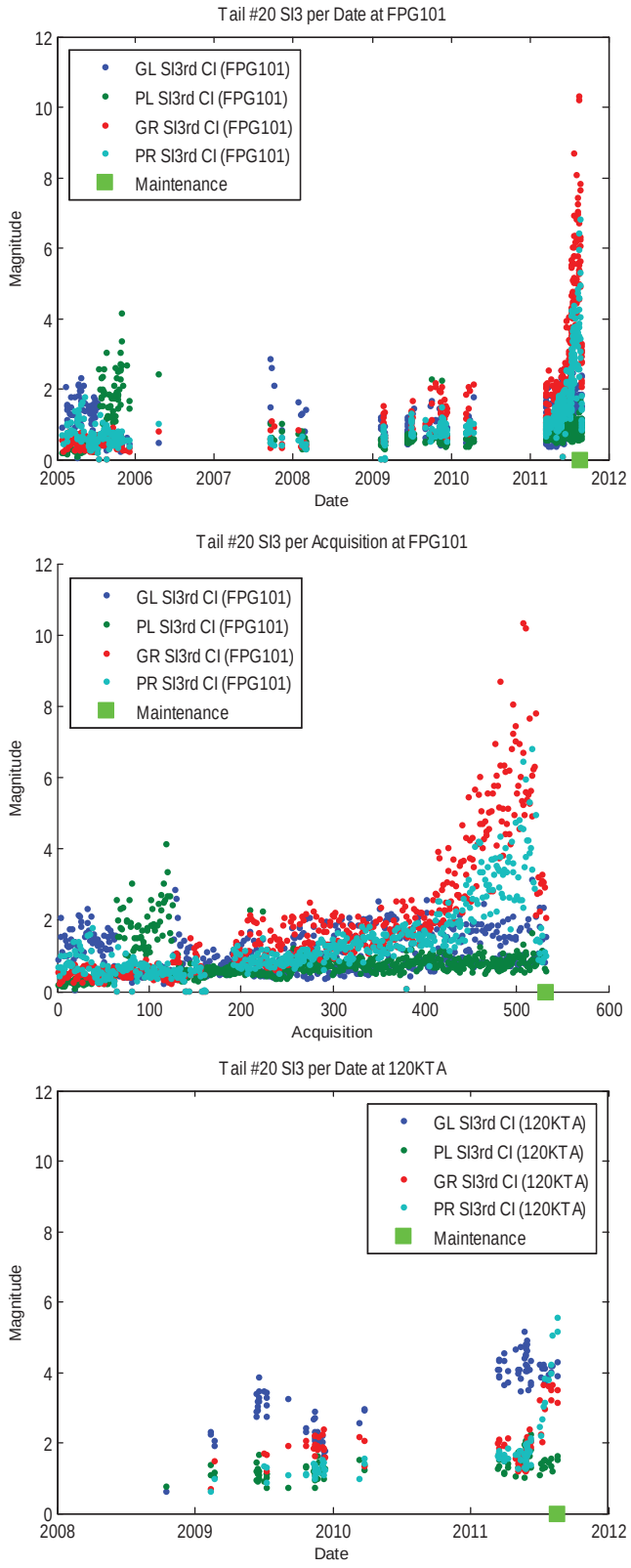

Figure A.20.4.—Tail Number 20 Plots of SI3 per Date, Acquisition and Regime

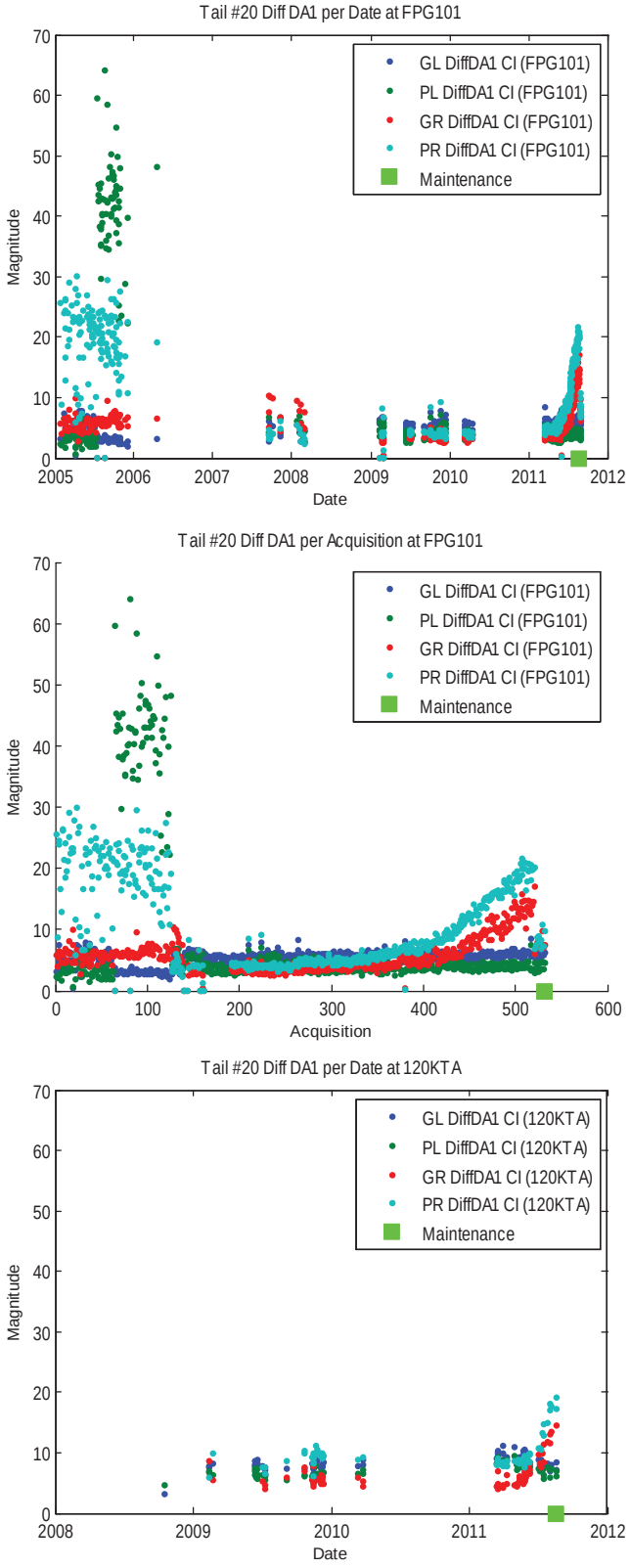

Figure A.20.5.—Tail Number 20 Plots of DiffDA1 per Date, Acquisition and Regime

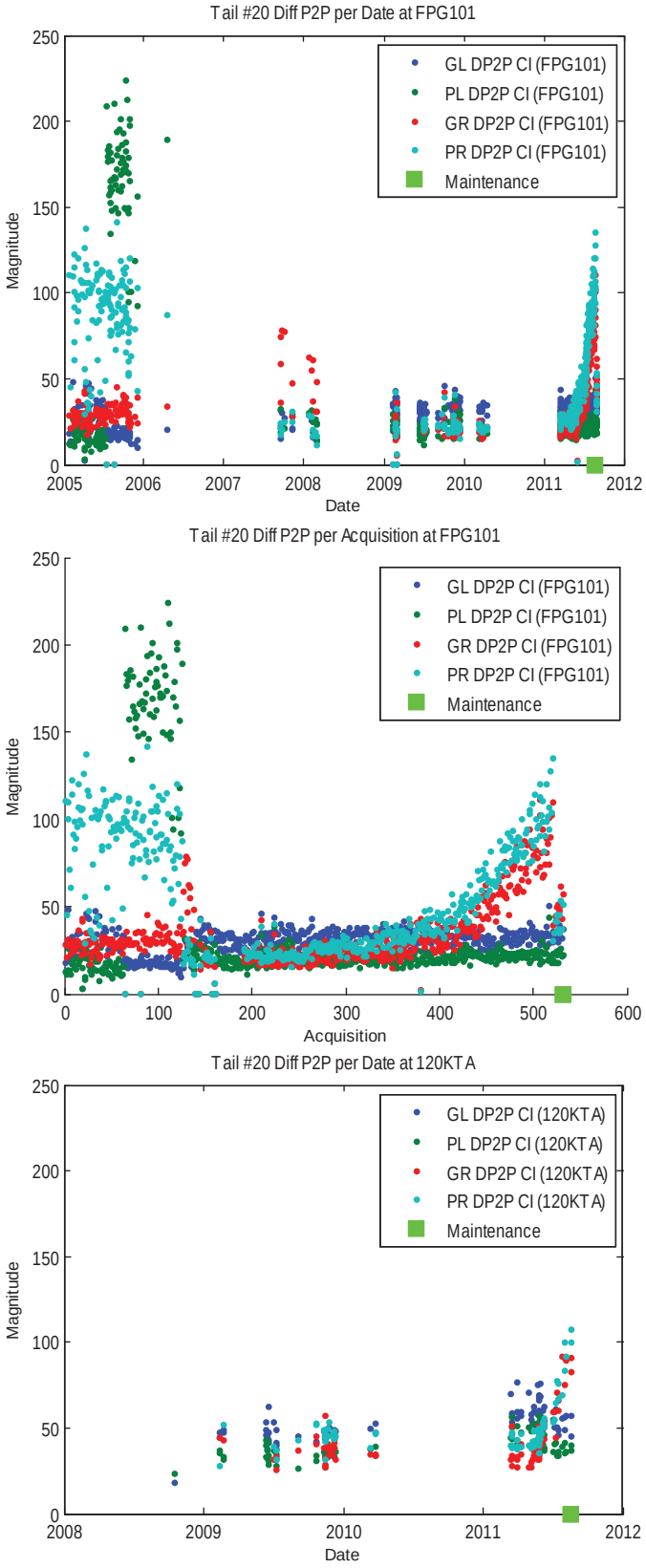

Figure A.20.6.—Tail Number 20 Plots of DP2P per Date, Acquisition and Regime

Appendix B.—CI Statistical Parameters Before and After Replacement

TABLE B.1.—TAIL NUMBER 1 STATISTICAL PARAMETERS—FPG101

Location	CI Name	Status	Index start	Index end	No. points	Mean	STD
PR	DA1	Before	1	159	159	6.98	2.81
PR	DA1	After	160	361	201	15.35	4.62
GR	DA1	Before	1	162	162	6.61	2.53
GR	DA1	After	163	364	201	14.66	5.13
PL	DA1	Before	1	159	159	17.63	6.51
PL	DA1	After	160	363	203	12.34	5.59
GL	DA1	Before	1	159	159	8.22	1.99
GL	DA1	After	160	363	203	11.68	5.84
PR	FM4	Before	1	160	160	2.97	0.41
PR	FM4	After	161	362	201	3.00	0.36
GR	FM4	Before	1	4	4	2.97	0.13
GR	FM4	After	5	206	201	2.93	0.25
PL	FM4	Before	1	160	160	2.15	0.21
PL	FM4	After	161	364	203	2.67	0.27
GL	FM4	Before	1	160	160	4.40	1.04
GL	FM4	After	161	364	203	2.96	0.24
PR	SI1st	Before	1	159	159	1.48	0.86
PR	SI1st	After	160	361	201	2.79	0.58
GR	SI1st	Before	1	162	162	0.95	0.60
GR	SI1st	After	163	364	201	2.41	0.72
PL	SI1st	Before	1	159	159	1.51	0.94
PL	SI1st	After	160	363	203	2.25	0.86
GL	SI1st	Before	1	159	159	0.79	0.42
GL	SI1st	After	160	363	203	1.47	0.66
PR	SI3rd	Before	1	159	159	0.77	0.37
PR	SI3rd	After	160	361	201	1.58	0.27
GR	SI3rd	Before	1	162	162	0.94	0.47
GR	SI3rd	After	163	364	201	1.84	0.58
PL	SI3rd	Before	1	159	159	0.97	0.45
PL	SI3rd	After	160	363	203	1.79	0.47
GL	SI3rd	Before	1	159	159	0.81	0.33
GL	SI3rd	After	160	363	203	1.74	0.42
PR	DiffDA1	Before	1	159	159	1.60	0.54
PR	DiffDA1	After	160	361	201	5.00	0.78
GR	DiffDA1	Before	1	162	162	2.39	0.97
GR	DiffDA1	After	163	364	201	4.05	0.90
PL	DiffDA1	Before	1	159	159	16.06	6.79
PL	DiffDA1	After	160	363	203	5.72	0.65
GL	DiffDA1	Before	1	159	159	5.42	1.48
GL	DiffDA1	After	160	363	203	4.99	0.81
PR	DP2P	Before	1	159	159	8.69	3.12
PR	DP2P	After	160	361	201	27.96	4.43
GR	DP2P	Before	1	162	162	13.71	5.80
GR	DP2P	After	163	364	201	23.97	5.80
PL	DP2P	Before	1	159	159	65.52	25.37
PL	DP2P	After	160	363	203	29.21	4.42
GL	DP2P	Before	1	159	159	40.81	15.61
GL	DP2P	After	160	363	203	29.25	4.82

TABLE B.2.—TAIL NUMBER 2 STATISTICAL PARAMETERS
(a) Number 2—FPG101

Location	CI Name	Status	Index start	Index end	No. points	Mean	STD
PR	DA1	Before	1	120	120	14.88	6.15
PR	DA1	After	121	493	372	9.12	1.87
GR	DA1	Before	1	120	120	14.87	6.60
GR	DA1	After	121	493	372	5.09	2.68
PL	DA1	Before	1	375	375	18.12	11.24
PL	DA1	After	376	763	387	19.47	5.79
GL	DA1	Before	1	375	375	18.13	11.01
GL	DA1	After	376	764	388	20.64	5.64
PR	FM4	Before	1	196	196	2.69	0.41
PR	FM4	After	197	569	372	1.73	0.14
GR	FM4	Before	1	196	196	2.78	0.23
GR	FM4	After	197	566	369	2.91	0.22
PL	FM4	Before	1	451	451	2.39	0.35
PL	FM4	After	452	834	382	2.76	0.27
GL	FM4	Before	1	451	451	2.84	0.23
GL	FM4	After	452	834	382	2.85	0.22
PR	SI1st	Before	1	120	120	1.34	0.58
PR	SI1st	After	121	493	372	0.74	0.41
GR	SI1st	Before	1	120	120	1.56	0.77
GR	SI1st	After	121	493	372	0.73	0.28
PL	SI1st	Before	1	375	375	1.56	0.75
PL	SI1st	After	376	763	387	1.56	0.66
GL	SI1st	Before	1	375	375	2.33	0.65
GL	SI1st	After	376	764	388	4.14	1.52
PR	SI3rd	Before	1	120	120	0.86	0.29
PR	SI3rd	After	121	493	372	0.43	0.18
GR	SI3rd	Before	1	120	120	1.71	0.75
GR	SI3rd	After	121	493	372	0.65	0.16
PL	SI3rd	Before	1	375	375	1.05	0.39
PL	SI3rd	After	376	763	387	1.00	0.25
GL	SI3rd	Before	1	375	375	1.92	0.33
GL	SI3rd	After	376	764	388	2.48	0.49
PR	DiffDA1	Before	1	120	120	4.93	2.12
PR	DiffDA1	After	121	493	372	7.82	1.22
GR	DiffDA1	Before	1	120	120	6.36	3.34
GR	DiffDA1	After	121	493	372	3.03	0.42
PL	DiffDA1	Before	1	375	375	7.55	2.04
PL	DiffDA1	After	376	763	387	4.90	0.56
GL	DiffDA1	Before	1	375	375	7.28	1.40
GL	DiffDA1	After	376	764	388	6.70	0.84
PR	DP2P	Before	1	120	120	25.00	10.57
PR	DP2P	After	121	493	372	29.13	4.05
GR	DP2P	Before	1	120	120	35.76	17.04
GR	DP2P	After	121	493	372	18.21	2.96
PL	DP2P	Before	1	375	375	36.78	10.64
PL	DP2P	After	376	763	387	26.27	3.67
GL	DP2P	Before	1	375	375	41.78	9.00
GL	DP2P	After	376	764	388	38.47	4.89

TABLE B.2.—CONCLUDED
(b) Number 2—120KTA

Location	CI name	Status	Index start	Index end	No. points	Mean	STD
PR	DA1	Before	1	118	118	11.82	2.80
PR	DA1	After	119	271	152	14.47	2.54
GR	DA1	Before	1	118	118	12.21	3.10
GR	DA1	After	119	271	152	12.94	2.91
PL	DA1	Before	1	274	274	50.24	11.74
PL	DA1	After	275	430	155	27.11	10.75
GL	DA1	Before	1	274	274	49.85	11.75
GL	DA1	After	275	430	155	27.63	10.45
PR	FM4	Before	1	118	118	2.80	0.36
PR	FM4	After	119	271	152	2.05	0.12
GR	FM4	Before	1	118	118	3.13	0.35
GR	FM4	After	119	271	152	3.20	0.28
PL	FM4	Before	1	274	274	2.98	0.28
PL	FM4	After	275	430	155	2.77	0.30
GL	FM4	Before	1	274	274	2.77	0.13
GL	FM4	After	275	430	155	2.91	0.18
PR	SI1st	Before	1	118	118	2.40	0.56
PR	SI1st	After	119	271	152	1.40	0.34
GR	SI1st	Before	1	118	118	1.42	0.61
GR	SI1st	After	119	271	152	1.38	0.27
PL	SI1st	Before	1	274	274	2.07	1.18
PL	SI1st	After	275	430	155	2.42	1.26
GL	SI1st	Before	1	274	274	3.21	1.21
GL	SI1st	After	275	430	155	4.13	1.61
PR	SI3rd	Before	1	118	118	1.37	0.24
PR	SI3rd	After	119	271	152	0.83	0.16
GR	SI3rd	Before	1	118	118	1.51	0.48
GR	SI3rd	After	119	271	152	0.99	0.15
PL	SI3rd	Before	1	274	274	1.50	0.72
PL	SI3rd	After	275	430	155	1.53	0.41
GL	SI3rd	Before	1	274	274	2.32	0.55
GL	SI3rd	After	275	430	155	2.46	0.45
PR	DiffDA1	Before	1	118	118	5.08	1.38
PR	DiffDA1	After	119	271	152	7.26	0.79
GR	DiffDA1	Before	1	118	118	6.20	2.11
GR	DiffDA1	After	119	271	152	3.69	0.25
PL	DiffDA1	Before	1	274	274	13.80	2.27
PL	DiffDA1	After	275	430	155	6.61	1.08
GL	DiffDA1	Before	1	274	274	12.01	1.20
GL	DiffDA1	After	275	430	155	7.27	0.73
PR	DP2P	Before	1	118	118	26.87	6.87
PR	DP2P	After	119	271	152	31.21	2.97
GR	DP2P	Before	1	118	118	39.11	12.96
GR	DP2P	After	119	271	152	23.88	2.39
PL	DP2P	Before	1	274	274	76.61	14.04
PL	DP2P	After	275	430	155	35.44	7.11
GL	DP2P	Before	1	274	274	74.67	10.57
GL	DP2P	After	275	430	155	45.39	5.50

TABLE B.3.—TAIL NUMBER 4 STATISTICAL PARAMETERS
(a) Number 4—FPG101

Location	CI name	Status	Index start	Index end	No. points	Mean	STD
PR	DA1	Before	1	25	25	26.05	9.18
PR	DA1	After	26	445	419	27.02	7.11
GR	DA1	Before	1	25	25	26.66	9.53
GR	DA1	After	26	445	419	27.45	7.15
PL	DA1	Before	1	25	25	66.98	19.42
PL	DA1	After	26	444	418	12.18	2.19
GL	DA1	Before	1	25	25	66.66	19.74
GL	DA1	After	26	445	419	11.13	2.31
PR	FM4	Before	1	25	25	2.85	0.26
PR	FM4	After	26	444	418	2.80	0.32
GR	FM4	Before	1	25	25	2.87	0.27
GR	FM4	After	26	444	418	2.92	0.28
PL	FM4	Before	1	25	25	2.83	0.34
PL	FM4	After	26	444	418	2.91	0.29
GL	FM4	Before	1	25	25	3.01	0.34
GL	FM4	After	26	444	418	3.22	0.40
PR	SI1st	Before	1	25	25	2.58	0.51
PR	SI1st	After	26	445	419	2.73	0.87
GR	SI1st	Before	1	25	25	3.38	1.55
GR	SI1st	After	26	445	419	2.59	1.29
PL	SI1st	Before	1	25	25	6.69	2.45
PL	SI1st	After	26	444	418	2.02	0.62
GL	SI1st	Before	1	25	25	5.68	2.00
GL	SI1st	After	26	445	419	1.25	0.50
PR	SI3rd	Before	1	25	25	1.34	0.21
PR	SI3rd	After	26	445	419	1.51	0.33
GR	SI3rd	Before	1	25	25	3.17	1.30
GR	SI3rd	After	26	445	419	2.60	0.98
PL	SI3rd	Before	1	25	25	4.33	1.42
PL	SI3rd	After	26	444	418	1.39	0.29
GL	SI3rd	Before	1	25	25	4.17	0.95
GL	SI3rd	After	26	445	419	1.35	0.32
PR	DiffDA1	Before	1	25	25	5.61	0.68
PR	DiffDA1	After	26	445	419	5.54	0.59
GR	DiffDA1	Before	1	25	25	7.51	2.13
GR	DiffDA1	After	26	445	419	6.94	1.56
PL	DiffDA1	Before	1	25	25	14.17	3.32
PL	DiffDA1	After	26	444	418	6.64	1.05
GL	DiffDA1	Before	1	25	25	12.34	2.79
GL	DiffDA1	After	26	445	419	4.78	0.60
PR	DP2P	Before	1	25	25	30.02	4.77
PR	DP2P	After	26	445	419	29.94	4.16
GR	DP2P	Before	1	25	25	42.32	10.68
GR	DP2P	After	26	445	419	40.43	7.69
PL	DP2P	Before	1	25	25	74.48	17.70
PL	DP2P	After	26	444	418	35.43	5.63
GL	DP2P	Before	1	25	25	75.34	17.94
GL	DP2P	After	26	445	419	30.16	3.59

TABLE B.3.—CONCLUDED
(b) Number 4—120KTA

Location	CI name	Status	Index start	Index end	No. points	Mean	STD
PR	DA1	Before	1	15	15	23.15	2.94
PR	DA1	After	16	74	58	19.06	5.34
GR	DA1	Before	1	15	15	23.91	2.68
GR	DA1	After	16	74	58	19.74	5.15
PL	DA1	Before	1	15	15	81.22	4.78
PL	DA1	After	16	74	58	17.92	1.98
GL	DA1	Before	1	15	15	81.23	4.52
GL	DA1	After	16	74	58	17.68	2.07
PR	FM4	Before	1	15	15	2.53	0.17
PR	FM4	After	16	74	58	2.69	0.18
GR	FM4	Before	1	15	15	2.80	0.18
GR	FM4	After	16	74	58	3.10	0.27
PL	FM4	Before	1	15	15	2.73	0.22
PL	FM4	After	16	74	58	2.78	0.20
GL	FM4	Before	1	15	15	3.34	0.24
GL	FM4	After	16	74	58	3.04	0.19
PR	SI1st	Before	1	15	15	1.35	0.38
PR	SI1st	After	16	74	58	1.58	0.50
GR	SI1st	Before	1	15	15	3.50	0.39
GR	SI1st	After	16	74	58	2.80	0.64
PL	SI1st	Before	1	15	15	5.46	1.00
PL	SI1st	After	16	74	58	1.90	0.48
GL	SI1st	Before	1	15	15	5.96	0.65
GL	SI1st	After	16	74	58	1.78	0.61
PR	SI3rd	Before	1	15	15	1.16	0.15
PR	SI3rd	After	16	74	58	1.26	0.24
GR	SI3rd	Before	1	15	15	4.00	0.36
GR	SI3rd	After	16	74	58	3.42	0.54
PL	SI3rd	Before	1	15	15	4.39	0.56
PL	SI3rd	After	16	74	58	1.43	0.18
GL	SI3rd	Before	1	15	15	3.48	0.26
GL	SI3rd	After	16	74	58	1.75	0.36
PR	DiffDA1	Before	1	15	15	6.69	0.25
PR	DiffDA1	After	16	74	58	6.04	0.72
GR	DiffDA1	Before	1	15	15	8.59	0.81
GR	DiffDA1	After	16	74	58	7.48	1.11
PL	DiffDA1	Before	1	15	15	15.92	1.58
PL	DiffDA1	After	16	74	58	6.89	0.31
GL	DiffDA1	Before	1	15	15	12.78	0.75
GL	DiffDA1	After	16	74	58	5.99	0.63
PR	DP2P	Before	1	15	15	34.83	2.23
PR	DP2P	After	16	74	58	31.69	4.33
GR	DP2P	Before	1	15	15	48.72	3.74
GR	DP2P	After	16	74	58	47.50	6.52
PL	DP2P	Before	1	15	15	84.17	10.97
PL	DP2P	After	16	74	58	36.78	2.89
GL	DP2P	Before	1	15	15	87.55	7.43
GL	DP2P	After	16	74	58	38.69	5.35

TABLE B.4.—TAIL NUMBER 5 STATISTICAL PARAMETERS
(a) Number 5—FPG101

Location	CI name	Status	Index start	Index end	No. points	Mean	STD
PR	DA1	Before	1	14	14	17.55	3.95
PR	DA1	After	15	85	70	18.63	6.75
GR	DA1	Before	1	14	14	18.71	4.04
GR	DA1	After	15	85	70	19.69	6.38
PL	DA1	Before	1	14	14	38.39	7.08
PL	DA1	After	15	85	70	11.77	9.21
GL	DA1	Before	1	14	14	30.32	5.58
GL	DA1	After	15	86	71	12.36	8.81
PR	FM4	Before	1	14	14	2.96	0.26
PR	FM4	After	15	85	70	2.80	0.29
GR	FM4	Before	1	14	14	2.90	0.17
GR	FM4	After	15	85	70	2.81	0.20
PL	FM4	Before	1	14	14	2.58	0.18
PL	FM4	After	15	85	70	2.77	0.33
GL	FM4	Before	1	14	14	3.06	0.43
GL	FM4	After	15	85	70	2.78	0.18
PR	SI1st	Before	1	14	14	1.57	0.47
PR	SI1st	After	15	85	70	1.33	0.90
GR	SI1st	Before	1	14	14	1.72	0.75
GR	SI1st	After	15	85	70	1.94	0.95
PL	SI1st	Before	1	14	14	7.77	1.81
PL	SI1st	After	15	85	70	1.08	0.57
GL	SI1st	Before	1	14	14	2.78	0.56
GL	SI1st	After	15	86	71	1.37	0.63
PR	SI3rd	Before	1	14	14	0.97	0.15
PR	SI3rd	After	15	85	70	0.99	0.32
GR	SI3rd	Before	1	14	14	1.78	0.55
GR	SI3rd	After	15	85	70	1.66	0.39
PL	SI3rd	Before	1	14	14	5.02	0.92
PL	SI3rd	After	15	85	70	0.80	0.26
GL	SI3rd	Before	1	14	14	1.99	0.37
GL	SI3rd	After	15	86	71	1.28	0.29
PR	DiffDA1	Before	1	14	14	3.89	0.48
PR	DiffDA1	After	15	85	70	3.59	0.82
GR	DiffDA1	Before	1	14	14	7.28	1.02
GR	DiffDA1	After	15	85	70	6.77	0.89
PL	DiffDA1	Before	1	14	14	22.74	4.70
PL	DiffDA1	After	15	85	70	4.11	1.18
GL	DiffDA1	Before	1	14	14	7.27	0.60
GL	DiffDA1	After	15	86	71	5.08	0.87
PR	DP2P	Before	1	14	14	21.59	2.64
PR	DP2P	After	15	85	70	19.39	4.65
GR	DP2P	Before	1	14	14	43.09	6.42
GR	DP2P	After	15	85	70	39.46	5.97
PL	DP2P	Before	1	14	14	109.21	21.98
PL	DP2P	After	15	85	70	21.63	5.77
GL	DP2P	Before	1	14	14	45.21	7.36
GL	DP2P	After	15	86	71	28.36	5.80

TABLE B.4.—CONCLUDED
(b) Number 5—120KTA

Location	CI name	Status	Index start	Index end	No. points	Mean	STD
PR	DA1	Before	1	2	2	38.29	1.05
PR	DA1	After	3	16	13	42.25	26.77
GR	DA1	Before	1	2	2	40.47	1.39
GR	DA1	After	3	16	13	43.21	26.27
PL	DA1	Before	1	2	2	63.39	3.57
PL	DA1	After	3	16	13	29.08	13.37
GL	DA1	Before	1	2	2	48.56	2.37
GL	DA1	After	3	16	13	29.50	12.88
PR	FM4	Before	1	2	2	3.10	0.10
PR	FM4	After	3	16	13	2.98	0.46
GR	FM4	Before	1	2	2	2.65	0.06
GR	FM4	After	3	16	13	2.95	0.17
PL	FM4	Before	1	2	2	2.65	0.32
PL	FM4	After	3	16	13	2.72	0.54
GL	FM4	Before	1	2	2	2.80	0.10
GL	FM4	After	3	16	13	2.87	0.16
PR	SI1st	Before	1	2	2	1.38	0.22
PR	SI1st	After	3	16	13	3.39	1.49
GR	SI1st	Before	1	2	2	4.23	0.83
GR	SI1st	After	3	16	13	1.64	0.60
PL	SI1st	Before	1	2	2	10.99	0.97
PL	SI1st	After	3	16	13	1.62	0.32
GL	SI1st	Before	1	2	2	4.58	1.37
GL	SI1st	After	3	16	13	1.88	0.60
PR	SI3rd	Before	1	2	2	0.99	0.16
PR	SI3rd	After	3	16	13	1.79	0.48
GR	SI3rd	Before	1	2	2	3.14	0.04
GR	SI3rd	After	3	16	13	2.59	0.70
PL	SI3rd	Before	1	2	2	9.56	0.22
PL	SI3rd	After	3	16	13	1.14	0.17
GL	SI3rd	Before	1	2	2	2.68	0.38
GL	SI3rd	After	3	16	13	1.62	0.42
PR	DiffDA1	Before	1	2	2	6.65	1.11
PR	DiffDA1	After	3	16	13	6.79	2.82
GR	DiffDA1	Before	1	2	2	10.53	0.27
GR	DiffDA1	After	3	16	13	10.26	2.65
PL	DiffDA1	Before	1	2	2	39.21	2.21
PL	DiffDA1	After	3	16	13	9.24	1.72
GL	DiffDA1	Before	1	2	2	11.19	0.29
GL	DiffDA1	After	3	16	13	8.73	1.30
PR	DP2P	Before	1	2	2	39.29	8.65
PR	DP2P	After	3	16	13	37.12	14.22
GR	DP2P	Before	1	2	2	62.92	2.06
GR	DP2P	After	3	16	13	64.32	18.45
PL	DP2P	Before	1	2	2	207.27	35.69
PL	DP2P	After	3	16	13	48.58	7.54
GL	DP2P	Before	1	2	2	66.77	0.14
GL	DP2P	After	3	16	13	53.38	6.42

TABLE B.5.—TAIL NUMBER 6 STATISTICAL PARAMETERS
(a) Number 6—FPG101

Location	CI name	Status	Index start	Index end	No. points	Mean	STD
PR	DA1	Before	1	39	39	36.10	5.51
PR	DA1	After	40	759	719	13.53	4.84
GR	DA1	Before	1	39	39	34.60	5.59
GR	DA1	After	40	754	714	14.49	4.45
PL	DA1	Before	1	39	39	17.15	4.60
PL	DA1	After	40	752	712	22.54	21.51
GL	DA1	Before	1	39	39	17.08	4.65
GL	DA1	After	40	760	720	23.95	21.18
PR	FM4	Before	1	39	39	2.98	0.25
PR	FM4	After	40	751	711	2.80	0.31
GR	FM4	Before	1	39	39	2.51	0.21
GR	FM4	After	40	749	709	3.03	0.27
PL	FM4	Before	1	39	39	2.73	0.22
PL	FM4	After	40	745	705	2.90	0.33
GL	FM4	Before	1	39	39	2.95	0.35
GL	FM4	After	40	745	705	2.92	0.33
PR	SI1st	Before	1	39	39	6.65	1.37
PR	SI1st	After	40	759	719	1.75	0.78
GR	SI1st	Before	1	39	39	3.04	0.33
GR	SI1st	After	40	754	714	2.06	0.92
PL	SI1st	Before	1	39	39	0.61	0.19
PL	SI1st	After	40	752	712	2.96	3.12
GL	SI1st	Before	1	39	39	1.76	0.67
GL	SI1st	After	40	760	720	5.26	3.05
PR	SI3rd	Before	1	39	39	4.09	0.52
PR	SI3rd	After	40	759	719	0.98	0.32
GR	SI3rd	Before	1	39	39	2.83	0.30
GR	SI3rd	After	40	754	714	1.93	0.49
PL	SI3rd	Before	1	39	39	0.63	0.16
PL	SI3rd	After	40	752	712	1.95	1.58
GL	SI3rd	Before	1	39	39	1.15	0.41
GL	SI3rd	After	40	760	720	3.22	1.67
PR	DiffDA1	Before	1	39	39	14.96	1.17
PR	DiffDA1	After	40	759	719	3.43	0.65
GR	DiffDA1	Before	1	39	39	11.72	1.43
GR	DiffDA1	After	40	754	714	5.95	0.76
PL	DiffDA1	Before	1	39	39	5.08	0.59
PL	DiffDA1	After	40	752	712	5.96	2.86
GL	DiffDA1	Before	1	39	39	4.29	0.52
GL	DiffDA1	After	40	760	720	7.26	2.52
PR	DP2P	Before	1	39	39	82.52	9.51
PR	DP2P	After	40	759	719	18.33	3.53
GR	DP2P	Before	1	39	39	63.46	5.11
GR	DP2P	After	40	754	714	36.25	4.87
PL	DP2P	Before	1	39	39	26.77	3.41
PL	DP2P	After	40	752	712	32.54	16.24
GL	DP2P	Before	1	39	39	25.91	4.86
GL	DP2P	After	40	760	720	42.94	15.89

TABLE B.5.—CONCLUDED
(a) Number 6—FPG101

Location	CI name	Status	Index start	Index end	No. points	Mean	STD
PR	DA1	Before	1	33	33	32.39	5.76
PR	DA1	After	34	266	232	33.53	8.91
GR	DA1	Before	1	33	33	34.02	5.84
GR	DA1	After	34	266	232	34.81	8.64
PL	DA1	Before	1	33	33	6.63	0.58
PL	DA1	After	34	266	232	24.63	17.96
GL	DA1	Before	1	33	33	6.54	0.61
GL	DA1	After	34	266	232	25.68	17.58
PR	FM4	Before	1	33	33	3.07	0.32
PR	FM4	After	34	266	232	2.76	0.29
GR	FM4	Before	1	33	33	2.06	0.08
GR	FM4	After	34	266	232	2.83	0.27
PL	FM4	Before	1	33	33	2.17	0.12
PL	FM4	After	34	266	232	2.78	0.45
GL	FM4	Before	1	33	33	3.38	0.19
GL	FM4	After	34	266	232	2.88	0.33
PR	SI1st	Before	1	33	33	10.17	1.10
PR	SI1st	After	34	266	232	2.63	1.19
GR	SI1st	Before	1	33	33	2.23	0.61
GR	SI1st	After	34	266	232	4.09	1.19
PL	SI1st	Before	1	33	33	0.40	0.13
PL	SI1st	After	34	266	232	2.34	2.21
GL	SI1st	Before	1	33	33	1.58	0.21
GL	SI1st	After	34	266	232	4.01	2.29
PR	SI3rd	Before	1	33	33	4.84	0.53
PR	SI3rd	After	34	266	232	1.57	0.43
GR	SI3rd	Before	1	33	33	2.30	0.39
GR	SI3rd	After	34	266	232	3.54	0.80
PL	SI3rd	Before	1	33	33	0.40	0.06
PL	SI3rd	After	34	266	232	1.53	1.11
GL	SI3rd	Before	1	33	33	0.93	0.10
GL	SI3rd	After	34	266	232	2.93	1.16
PR	DiffDA1	Before	1	33	33	10.22	0.78
PR	DiffDA1	After	34	266	232	6.77	1.05
GR	DiffDA1	Before	1	33	33	17.90	1.00
GR	DiffDA1	After	34	266	232	10.20	1.93
PL	DiffDA1	Before	1	33	33	5.74	0.37
PL	DiffDA1	After	34	266	232	6.17	2.46
GL	DiffDA1	Before	1	33	33	5.38	0.26
GL	DiffDA1	After	34	266	232	7.96	1.97
PR	DP2P	Before	1	33	33	57.08	6.49
PR	DP2P	After	34	266	232	36.70	6.80
GR	DP2P	Before	1	33	33	83.98	6.89
GR	DP2P	After	34	266	232	62.17	9.61
PL	DP2P	Before	1	33	33	27.53	1.87
PL	DP2P	After	34	266	232	33.26	14.25
GL	DP2P	Before	1	33	33	37.15	2.72
GL	DP2P	After	34	266	232	48.67	11.70

TABLE B.6.—TAIL NUMBER 7 STATISTICAL PARAMETERS—FPG101

Location	CI name	Status	Index start	Index end	No. points	Mean	STD
PR	DA1	Before	1	13	13	40.72	4.62
PR	DA1	After	14	1063	1049	27.56	7.99
GR	DA1	Before	1	13	13	35.20	4.54
GR	DA1	After	14	1061	1047	14.18	5.96
PL	DA1	Before	1	13	13	11.37	4.65
PL	DA1	After	14	1061	1047	7.51	3.13
GL	DA1	Before	1	13	13	11.45	4.42
GL	DA1	After	14	1063	1049	9.96	2.92
PR	FM4	Before	1	13	13	2.47	0.19
PR	FM4	After	14	1061	1047	2.78	0.39
GR	FM4	Before	1	13	13	4.55	0.54
GR	FM4	After	14	1060	1046	3.00	0.31
PL	FM4	Before	1	13	13	2.59	0.17
PL	FM4	After	14	1051	1037	2.92	0.36
GL	FM4	Before	1	13	13	2.93	0.14
GL	FM4	After	14	1051	1037	2.62	0.18
PR	SI1st	Before	1	13	13	3.27	1.00
PR	SI1st	After	14	1063	1049	1.88	0.86
GR	SI1st	Before	1	13	13	4.51	0.94
GR	SI1st	After	14	1061	1047	1.66	0.83
PL	SI1st	Before	1	13	13	1.17	0.34
PL	SI1st	After	14	1061	1047	0.66	0.26
GL	SI1st	Before	1	13	13	1.50	0.67
GL	SI1st	After	14	1063	1049	1.19	0.43
PR	SI3rd	Before	1	13	13	2.49	0.39
PR	SI3rd	After	14	1063	1049	1.41	0.50
GR	SI3rd	Before	1	13	13	2.89	0.52
GR	SI3rd	After	14	1061	1047	1.01	0.40
PL	SI3rd	Before	1	13	13	0.88	0.15
PL	SI3rd	After	14	1061	1047	0.53	0.16
GL	SI3rd	Before	1	13	13	1.28	0.19
GL	SI3rd	After	14	1063	1049	1.11	0.32
PR	DiffDA1	Before	1	13	13	27.65	4.21
PR	DiffDA1	After	14	1063	1049	23.46	6.86
GR	DiffDA1	Before	1	13	13	18.58	1.01
GR	DiffDA1	After	14	1061	1047	3.55	0.89
PL	DiffDA1	Before	1	13	13	3.78	0.52
PL	DiffDA1	After	14	1061	1047	2.79	0.61
GL	DiffDA1	Before	1	13	13	3.92	0.26
GL	DiffDA1	After	14	1063	1049	6.77	1.03
PR	DP2P	Before	1	13	13	130.34	17.82
PR	DP2P	After	14	1063	1049	119.99	33.86
GR	DP2P	Before	1	13	13	135.61	15.63
GR	DP2P	After	14	1061	1047	21.50	5.70
PL	DP2P	Before	1	13	13	19.09	3.05
PL	DP2P	After	14	1061	1047	15.50	3.70
GL	DP2P	Before	1	13	13	23.05	1.61
GL	DP2P	After	14	1063	1049	37.42	7.17

TABLE B.7.—TAIL NUMBER 8 STATISTICAL PARAMETERS

(a) Number 8—FPG101

Location	CI name	Status	Index start	Index end	No. points	Mean	STD
PR	DA1	Before	1	61	61	13.35	7.88
PR	DA1	After	62	392	330	29.75	4.82
GR	DA1	Before	1	61	61	13.26	7.48
GR	DA1	After	62	391	329	31.60	4.82
PL	DA1	Before	1	109	109	11.98	3.96
PL	DA1	After	110	439	329	10.01	6.55
GL	DA1	Before	1	109	109	12.44	3.80
GL	DA1	After	110	440	330	8.77	2.96
PR	FM4	Before	1	61	61	2.80	0.28
PR	FM4	After	62	391	329	2.91	0.36
GR	FM4	Before	1	61	61	2.89	0.21
GR	FM4	After	62	390	328	2.47	0.27
PL	FM4	Before	1	106	106	2.71	0.31
PL	FM4	After	107	434	327	2.74	0.36
GL	FM4	Before	1	106	106	2.81	0.35
GL	FM4	After	107	434	327	2.91	0.28
PR	SI1st	Before	1	61	61	2.98	2.28
PR	SI1st	After	62	392	330	1.18	0.42
GR	SI1st	Before	1	61	61	1.76	0.72
GR	SI1st	After	62	391	329	2.51	1.13
PL	SI1st	Before	1	109	109	1.55	0.54
PL	SI1st	After	110	439	329	1.72	0.65
GL	SI1st	Before	1	109	109	2.38	1.03
GL	SI1st	After	110	440	330	0.94	0.43
PR	SI3rd	Before	1	61	61	1.48	1.07
PR	SI3rd	After	62	392	330	0.84	0.20
GR	SI3rd	Before	1	61	61	1.64	0.71
GR	SI3rd	After	62	391	329	1.86	0.68
PL	SI3rd	Before	1	109	109	0.84	0.26
PL	SI3rd	After	110	439	329	0.94	0.30
GL	SI3rd	Before	1	109	109	1.89	0.66
GL	SI3rd	After	110	440	330	1.28	0.40
PR	DiffDA1	Before	1	61	61	3.06	1.31
PR	DiffDA1	After	62	392	330	4.39	0.58
GR	DiffDA1	Before	1	61	61	4.07	1.24
GR	DiffDA1	After	62	391	329	10.10	1.46
PL	DiffDA1	Before	1	109	109	3.93	1.10
PL	DiffDA1	After	110	439	329	5.80	7.09
GL	DiffDA1	Before	1	109	109	4.73	1.03
GL	DiffDA1	After	110	440	330	5.29	0.69
PR	DP2P	Before	1	61	61	16.64	7.46
PR	DP2P	After	62	392	330	24.05	3.86
GR	DP2P	Before	1	61	61	24.06	7.07
GR	DP2P	After	62	391	329	53.19	7.79
PL	DP2P	Before	1	109	109	20.44	5.46
PL	DP2P	After	110	439	329	27.22	27.80
GL	DP2P	Before	1	109	109	26.84	4.78
GL	DP2P	After	110	440	330	31.41	4.72

TABLE B.7.—CONCLUDED
(b) Number 8—120KTA

Location	CI name	Status	Index start	Index end	No. points	Mean	STD
PR	DA1	Before	1	60	60	24.47	4.50
PR	DA1	After	61	138	77	47.66	10.30
GR	DA1	Before	1	60	60	24.23	4.11
GR	DA1	After	61	138	77	49.14	9.83
PL	DA1	Before	1	71	71	23.38	5.31
PL	DA1	After	72	149	77	33.93	7.55
GL	DA1	Before	1	71	71	23.49	5.39
GL	DA1	After	72	149	77	33.52	8.87
PR	FM4	Before	1	60	60	3.06	0.45
PR	FM4	After	61	138	77	3.20	0.49
GR	FM4	Before	1	60	60	3.15	0.35
GR	FM4	After	61	138	77	3.13	0.19
PL	FM4	Before	1	71	71	2.74	0.25
PL	FM4	After	72	149	77	2.97	0.40
GL	FM4	Before	1	71	71	2.88	0.23
GL	FM4	After	72	149	77	2.93	0.19
PR	SI1st	Before	1	60	60	4.16	1.41
PR	SI1st	After	61	138	77	1.98	0.69
GR	SI1st	Before	1	60	60	2.96	0.61
GR	SI1st	After	61	138	77	3.77	1.26
PL	SI1st	Before	1	71	71	1.22	0.38
PL	SI1st	After	72	149	77	3.55	1.26
GL	SI1st	Before	1	71	71	2.12	1.00
GL	SI1st	After	72	149	77	1.61	0.53
PR	SI3rd	Before	1	60	60	2.10	0.90
PR	SI3rd	After	61	138	77	1.43	0.36
GR	SI3rd	Before	1	60	60	2.06	0.34
GR	SI3rd	After	61	138	77	3.18	0.59
PL	SI3rd	Before	1	71	71	0.77	0.19
PL	SI3rd	After	72	149	77	2.23	0.65
GL	SI3rd	Before	1	71	71	1.90	0.66
GL	SI3rd	After	72	149	77	1.88	0.44
PR	DiffDA1	Before	1	60	60	4.74	2.46
PR	DiffDA1	After	61	138	77	6.46	1.19
GR	DiffDA1	Before	1	60	60	5.27	0.61
GR	DiffDA1	After	61	138	77	11.01	1.03
PL	DiffDA1	Before	1	71	71	5.59	1.21
PL	DiffDA1	After	72	149	77	7.34	4.48
GL	DiffDA1	Before	1	71	71	5.98	0.95
GL	DiffDA1	After	72	149	77	8.01	0.93
PR	DP2P	Before	1	60	60	25.95	10.17
PR	DP2P	After	61	138	77	37.83	8.22
GR	DP2P	Before	1	60	60	34.91	5.36
GR	DP2P	After	61	138	77	72.45	8.28
PL	DP2P	Before	1	71	71	29.56	5.82
PL	DP2P	After	72	149	77	39.27	17.63
GL	DP2P	Before	1	71	71	37.37	5.73
GL	DP2P	After	72	149	77	51.50	8.68

TABLE B.8.—TAIL NUMBER 10 STATISTICAL PARAMETERS
(a) Number 10—FPG101

Location	CI name	Status	Index start	Index end	No. points	Mean	STD
PR	DA1	Before	1	108	108	12.75	4.38
PR	DA1	After	109	169	60	9.20	3.16
GR	DA1	Before	1	108	108	11.44	3.17
GR	DA1	After	109	169	60	10.44	2.85
PL	DA1	Before	1	108	108	18.67	3.15
PL	DA1	After	109	169	60	12.20	2.74
GL	DA1	Before	1	108	108	18.88	3.18
GL	DA1	After	109	169	60	12.21	2.80
PR	FM4	Before	1	108	108	2.79	0.39
PR	FM4	After	109	169	60	2.93	0.25
GR	FM4	Before	1	108	108	2.88	0.23
GR	FM4	After	109	169	60	2.98	0.20
PL	FM4	Before	1	107	107	2.69	0.33
PL	FM4	After	108	168	60	2.62	0.26
GL	FM4	Before	1	107	107	3.02	0.23
GL	FM4	After	108	168	60	2.93	0.23
PR	SI1st	Before	1	108	108	1.12	0.69
PR	SI1st	After	109	169	60	1.02	0.62
GR	SI1st	Before	1	108	108	1.68	0.88
GR	SI1st	After	109	169	60	1.13	0.39
PL	SI1st	Before	1	108	108	0.77	0.30
PL	SI1st	After	109	169	60	1.30	0.45
GL	SI1st	Before	1	108	108	1.69	0.44
GL	SI1st	After	109	169	60	1.49	0.57
PR	SI3rd	Before	1	108	108	1.02	0.50
PR	SI3rd	After	109	169	60	0.57	0.20
GR	SI3rd	Before	1	108	108	1.24	0.43
GR	SI3rd	After	109	169	60	1.14	0.36
PL	SI3rd	Before	1	108	108	0.88	0.19
PL	SI3rd	After	109	169	60	1.18	0.30
GL	SI3rd	Before	1	108	108	1.28	0.25
GL	SI3rd	After	109	169	60	1.25	0.24
PR	DiffDA1	Before	1	108	108	7.73	3.41
PR	DiffDA1	After	109	169	60	5.57	0.99
GR	DiffDA1	Before	1	108	108	5.09	1.23
GR	DiffDA1	After	109	169	60	7.35	0.93
PL	DiffDA1	Before	1	108	108	4.92	0.48
PL	DiffDA1	After	109	169	60	4.74	0.54
GL	DiffDA1	Before	1	108	108	4.82	0.51
GL	DiffDA1	After	109	169	60	4.56	0.38
PR	DP2P	Before	1	108	108	40.67	16.44
PR	DP2P	After	109	169	60	30.50	5.81
GR	DP2P	Before	1	108	108	29.75	7.68
GR	DP2P	After	109	169	60	43.79	6.31
PL	DP2P	Before	1	108	108	25.58	3.53
PL	DP2P	After	109	169	60	24.54	3.79
GL	DP2P	Before	1	108	108	29.31	3.85
GL	DP2P	After	109	169	60	26.36	2.49

TABLE B.8.—CONCLUDED
(b) Number 10—120KTA

Location	CI name	Status	Index start	Index end	No. points	Mean	STD
PR	DA1	Before	1	57	57	21.35	2.49
PR	DA1	After	58	86	28	26.16	4.06
GR	DA1	Before	1	57	57	15.91	2.04
GR	DA1	After	58	86	28	25.88	4.33
PL	DA1	Before	1	57	57	16.56	3.56
PL	DA1	After	58	86	28	19.33	6.26
GL	DA1	Before	1	57	57	16.94	3.35
GL	DA1	After	58	86	28	19.90	5.64
PR	FM4	Before	1	57	57	2.48	0.16
PR	FM4	After	58	86	28	2.40	0.16
GR	FM4	Before	1	57	57	2.98	0.33
GR	FM4	After	58	86	28	3.03	0.16
PL	FM4	Before	1	57	57	3.19	0.37
PL	FM4	After	58	86	28	2.92	0.25
GL	FM4	Before	1	57	57	2.84	0.21
GL	FM4	After	58	86	28	2.64	0.25
PR	SI1st	Before	1	57	57	3.43	0.87
PR	SI1st	After	58	86	28	1.62	0.55
GR	SI1st	Before	1	57	57	4.23	1.58
GR	SI1st	After	58	86	28	1.86	0.48
PL	SI1st	Before	1	57	57	1.73	0.49
PL	SI1st	After	58	86	28	1.96	0.60
GL	SI1st	Before	1	57	57	1.96	0.56
GL	SI1st	After	58	86	28	2.91	0.50
PR	SI3rd	Before	1	57	57	3.10	1.15
PR	SI3rd	After	58	86	28	1.04	0.25
GR	SI3rd	Before	1	57	57	2.54	0.76
GR	SI3rd	After	58	86	28	1.74	0.30
PL	SI3rd	Before	1	57	57	1.25	0.21
PL	SI3rd	After	58	86	28	1.20	0.22
GL	SI3rd	Before	1	57	57	1.28	0.26
GL	SI3rd	After	58	86	28	1.63	0.19
PR	DiffDA1	Before	1	57	57	16.16	3.52
PR	DiffDA1	After	58	86	28	9.79	0.79
GR	DiffDA1	Before	1	57	57	7.72	0.74
GR	DiffDA1	After	58	86	28	9.09	0.76
PL	DiffDA1	Before	1	57	57	4.67	0.58
PL	DiffDA1	After	58	86	28	5.39	0.78
GL	DiffDA1	Before	1	57	57	5.72	0.46
GL	DiffDA1	After	58	86	28	6.48	0.45
PR	DP2P	Before	1	57	57	80.25	20.78
PR	DP2P	After	58	86	28	46.67	4.08
GR	DP2P	Before	1	57	57	47.74	8.65
GR	DP2P	After	58	86	28	59.67	5.11
PL	DP2P	Before	1	57	57	28.44	3.78
PL	DP2P	After	58	86	28	30.48	4.54
GL	DP2P	Before	1	57	57	35.32	3.22
GL	DP2P	After	58	86	28	37.44	4.46

TABLE B.9.——TAIL NUMBER 13 STATISTICAL PARAMETERS

(a) Number 13—FPG101

Location	CI name	Status	Index start	Index end	No. points	Mean	STD
PR	DA1	Before	1	88	88	75.48	53.14
PR	DA1	After	89	92	3	21.24	10.92
GR	DA1	Before	1	88	88	27.51	10.81
GR	DA1	After	89	92	3	21.17	12.91
PL	DA1	Before	1	88	88	14.26	5.47
PL	DA1	After	89	92	3	28.18	3.42
GL	DA1	Before	1	88	88	16.17	4.90
GL	DA1	After	89	92	3	28.52	2.23
PR	FM4	Before	1	88	88	2.64	0.35
PR	FM4	After	89	92	3	2.10	0.29
GR	FM4	Before	1	88	88	3.00	0.62
GR	FM4	After	89	92	3	3.16	0.26
PL	FM4	Before	1	87	87	2.83	0.32
PL	FM4	After	88	91	3	2.77	0.26
GL	FM4	Before	1	87	87	3.13	0.24
GL	FM4	After	88	91	3	3.07	0.17
PR	SI1st	Before	1	88	88	9.91	8.41
PR	SI1st	After	89	92	3	2.46	0.46
GR	SI1st	Before	1	88	88	1.56	0.90
GR	SI1st	After	89	92	3	3.14	2.10
PL	SI1st	Before	1	88	88	2.56	1.00
PL	SI1st	After	89	92	3	2.62	0.84
GL	SI1st	Before	1	88	88	3.99	1.23
GL	SI1st	After	89	92	3	4.42	1.04
PR	SI3rd	Before	1	88	88	6.48	4.09
PR	SI3rd	After	89	92	3	1.26	0.19
GR	SI3rd	Before	1	88	88	1.98	0.94
GR	SI3rd	After	89	92	3	2.73	1.03
PL	SI3rd	Before	1	88	88	1.45	0.44
PL	SI3rd	After	89	92	3	1.96	0.63
GL	SI3rd	Before	1	88	88	3.11	0.48
GL	SI3rd	After	89	92	3	3.33	0.49
PR	DiffDA1	Before	1	88	88	70.69	52.54
PR	DiffDA1	After	89	92	3	7.59	0.64
GR	DiffDA1	Before	1	88	88	18.44	5.42
GR	DiffDA1	After	89	92	3	6.97	1.22
PL	DiffDA1	Before	1	88	88	4.12	0.52
PL	DiffDA1	After	89	92	3	6.44	1.11
GL	DiffDA1	Before	1	88	88	7.37	0.51
GL	DiffDA1	After	89	92	3	8.22	0.55
PR	DP2P	Before	1	88	88	352.10	264.85
PR	DP2P	After	89	92	3	33.24	2.24
GR	DP2P	Before	1	88	88	110.01	43.48
GR	DP2P	After	89	92	3	41.76	8.64
PL	DP2P	Before	1	88	88	22.35	3.54
PL	DP2P	After	89	92	3	34.90	5.78
GL	DP2P	Before	1	88	88	46.35	4.13
GL	DP2P	After	89	92	3	52.81	3.73

TABLE B.9.—CONCLUDED
(b) Number 13—120KTA

Location	CI name	Status	Index start	Index end	No. points	Mean	STD
PR	DA1	Before	1	31	31	55.77	40.40
PR	DA1	After	32	32	0	8.80	0.00
GR	DA1	Before	1	31	31	40.65	12.03
GR	DA1	After	32	32	0	10.04	0.00
PL	DA1	Before	1	31	31	41.07	5.69
PL	DA1	After	32	32	0	52.73	0.00
GL	DA1	Before	1	31	31	41.69	5.67
GL	DA1	After	32	32	0	52.62	0.00
PR	FM4	Before	1	31	31	3.03	0.48
PR	FM4	After	32	32	0	2.56	0.00
GR	FM4	Before	1	31	31	3.06	1.52
GR	FM4	After	32	32	0	2.81	0.00
PL	FM4	Before	1	31	31	2.99	0.51
PL	FM4	After	32	32	0	2.45	0.00
GL	FM4	Before	1	31	31	3.08	0.17
GL	FM4	After	32	32	0	2.76	0.00
PR	SI1st	Before	1	31	31	9.01	7.18
PR	SI1st	After	32	32	0	2.81	0.00
GR	SI1st	Before	1	31	31	3.31	2.15
GR	SI1st	After	32	32	0	2.78	0.00
PL	SI1st	Before	1	31	31	2.17	0.54
PL	SI1st	After	32	32	0	2.33	0.00
GL	SI1st	Before	1	31	31	4.15	0.68
GL	SI1st	After	32	32	0	5.21	0.00
PR	SI3rd	Before	1	31	31	5.60	3.55
PR	SI3rd	After	32	32	0	2.06	0.00
GR	SI3rd	Before	1	31	31	2.96	1.46
GR	SI3rd	After	32	32	0	3.06	0.00
PL	SI3rd	Before	1	31	31	1.26	0.30
PL	SI3rd	After	32	32	0	1.51	0.00
GL	SI3rd	Before	1	31	31	2.45	0.42
GL	SI3rd	After	32	32	0	3.13	0.00
PR	DiffDA1	Before	1	31	31	45.89	40.88
PR	DiffDA1	After	32	32	0	5.94	0.00
GR	DiffDA1	Before	1	31	31	30.07	5.01
GR	DiffDA1	After	32	32	0	7.41	0.00
PL	DiffDA1	Before	1	31	31	7.26	0.87
PL	DiffDA1	After	32	32	0	9.20	0.00
GL	DiffDA1	Before	1	31	31	8.70	0.68
GL	DiffDA1	After	32	32	0	10.09	0.00
PR	DP2P	Before	1	31	31	265.33	244.90
PR	DP2P	After	32	32	0	30.06	0.00
GR	DP2P	Before	1	31	31	180.08	76.12
GR	DP2P	After	32	32	0	43.95	0.00
PL	DP2P	Before	1	31	31	40.20	6.02
PL	DP2P	After	32	32	0	41.43	0.00
GL	DP2P	Before	1	31	31	55.97	5.72
GL	DP2P	After	32	32	0	63.20	0.00

TABLE B.10.—FIGURE B.14.1.—TAIL NUMBER 14 STATISTICAL PARAMETERS
(a) Number 14—FPG101

Location	CI name	Status	Index start	Index end	No. points	Mean	STD
PR	DA1	Before	1	75	75	17.34	6.17
PR	DA1	After	76	370	294	22.19	6.23
GR	DA1	Before	1	75	75	17.18	4.38
GR	DA1	After	76	370	294	22.79	5.62
PL	DA1	Before	1	75	75	134.36	31.10
PL	DA1	After	76	569	493	7.71	2.57
GL	DA1	Before	1	75	75	133.65	32.22
GL	DA1	After	76	569	493	8.93	2.13
PR	FM4	Before	1	75	75	2.70	0.42
PR	FM4	After	76	370	294	2.87	0.39
GR	FM4	Before	1	75	75	2.52	0.32
GR	FM4	After	76	370	294	2.75	0.28
PL	FM4	Before	1	75	75	2.69	0.28
PL	FM4	After	76	564	488	2.65	0.33
GL	FM4	Before	1	75	75	3.53	0.40
GL	FM4	After	76	564	488	2.99	0.24
PR	SI1st	Before	1	75	75	3.06	0.96
PR	SI1st	After	76	370	294	3.21	1.41
GR	SI1st	Before	1	75	75	2.30	0.64
GR	SI1st	After	76	370	294	2.80	1.21
PL	SI1st	Before	1	75	75	6.93	3.63
PL	SI1st	After	76	569	493	1.12	0.43
GL	SI1st	Before	1	75	75	8.00	3.01
GL	SI1st	After	76	569	493	3.31	1.32
PR	SI3rd	Before	1	75	75	1.72	0.43
PR	SI3rd	After	76	370	294	1.83	0.63
GR	SI3rd	Before	1	75	75	1.72	0.43
GR	SI3rd	After	76	370	294	2.11	0.60
PL	SI3rd	Before	1	75	75	5.98	1.37
PL	SI3rd	After	76	569	493	0.68	0.16
GL	SI3rd	Before	1	75	75	5.73	1.37
GL	SI3rd	After	76	569	493	1.80	0.57
PR	DiffDA1	Before	1	75	75	6.25	2.67
PR	DiffDA1	After	76	370	294	5.55	1.50
GR	DiffDA1	Before	1	75	75	9.45	2.44
GR	DiffDA1	After	76	370	294	7.88	2.17
PL	DiffDA1	Before	1	75	75	27.40	3.32
PL	DiffDA1	After	76	569	493	3.00	0.46
GL	DiffDA1	Before	1	75	75	19.44	2.93
GL	DiffDA1	After	76	569	493	3.77	0.55
PR	DP2P	Before	1	75	75	31.49	10.53
PR	DP2P	After	76	370	294	30.15	7.50
GR	DP2P	Before	1	75	75	48.28	9.48
GR	DP2P	After	76	370	294	43.65	11.18
PL	DP2P	Before	1	75	75	144.01	20.84
PL	DP2P	After	76	569	493	15.35	2.67
GL	DP2P	Before	1	75	75	127.28	23.93
GL	DP2P	After	76	569	493	22.70	3.82

TABLE B.10.—CONCLUDED
(b) Number 14—120KTA

Location	CI name	Status	Index start	Index end	No. points	Mean	STD
PR	DA1	Before	1	24	24	25.07	6.97
PR	DA1	After	25	87	62	25.24	8.53
GR	DA1	Before	1	24	24	25.99	6.94
GR	DA1	After	25	87	62	25.71	8.31
PL	DA1	Before	1	24	24	98.94	33.41
PL	DA1	After	25	134	109	18.07	4.20
GL	DA1	Before	1	24	24	96.54	35.52
GL	DA1	After	25	134	109	19.16	4.04
PR	FM4	Before	1	24	24	2.79	0.22
PR	FM4	After	25	87	62	2.98	0.39
GR	FM4	Before	1	24	24	2.87	0.16
GR	FM4	After	25	87	62	2.91	0.26
PL	FM4	Before	1	24	24	2.71	0.29
PL	FM4	After	25	134	109	2.92	0.33
GL	FM4	Before	1	24	24	4.07	0.38
GL	FM4	After	25	134	109	2.90	0.18
PR	SI1st	Before	1	24	24	3.39	1.00
PR	SI1st	After	25	87	62	3.39	1.48
GR	SI1st	Before	1	24	24	3.71	0.97
GR	SI1st	After	25	87	62	2.98	1.55
PL	SI1st	Before	1	24	24	11.06	3.57
PL	SI1st	After	25	134	109	2.06	1.10
GL	SI1st	Before	1	24	24	10.19	0.95
GL	SI1st	After	25	134	109	4.88	1.14
PR	SI3rd	Before	1	24	24	1.74	0.45
PR	SI3rd	After	25	87	62	1.82	0.54
GR	SI3rd	Before	1	24	24	2.35	0.47
GR	SI3rd	After	25	87	62	2.17	0.78
PL	SI3rd	Before	1	24	24	8.32	1.18
PL	SI3rd	After	25	134	109	1.23	0.44
GL	SI3rd	Before	1	24	24	6.42	1.40
GL	SI3rd	After	25	134	109	2.87	0.44
PR	DiffDA1	Before	1	24	24	5.59	1.12
PR	DiffDA1	After	25	87	62	6.21	1.11
GR	DiffDA1	Before	1	24	24	7.65	1.65
GR	DiffDA1	After	25	87	62	7.88	1.65
PL	DiffDA1	Before	1	24	24	32.87	5.50
PL	DiffDA1	After	25	134	109	3.62	0.45
GL	DiffDA1	Before	1	24	24	25.08	3.01
GL	DiffDA1	After	25	134	109	5.25	0.40
PR	DP2P	Before	1	24	24	29.74	6.49
PR	DP2P	After	25	87	62	34.44	6.92
GR	DP2P	Before	1	24	24	47.81	11.45
GR	DP2P	After	25	87	62	49.76	9.96
PL	DP2P	Before	1	24	24	171.79	25.07
PL	DP2P	After	25	134	109	20.24	3.18
GL	DP2P	Before	1	24	24	185.36	27.92
GL	DP2P	After	25	134	109	32.81	3.50

TABLE B.11.—TAIL NUMBER 15 STATISTICAL PARAMETERS—FPG101

Location	CI name	Status	Index start	Index end	No. points	Mean	STD
PR	DA1	Before	1	54	54	6.52	2.27
PR	DA1	After	55	151	96	5.73	2.52
GR	DA1	Before	1	54	54	6.17	2.25
GR	DA1	After	55	151	96	5.42	2.09
PL	DA1	Before	1	60	60	36.52	19.57
PL	DA1	After	61	157	96	3.51	2.40
GL	DA1	Before	1	60	60	21.94	13.98
GL	DA1	After	61	157	96	4.21	1.55
PR	FM4	Before	1	93	93	2.64	0.34
PR	FM4	After	94	190	96	2.82	0.32
GR	FM4	Before	1	93	93	2.40	0.34
GR	FM4	After	94	190	96	2.44	0.26
PL	FM4	Before	1	99	99	2.73	0.39
PL	FM4	After	100	196	96	2.88	0.41
GL	FM4	Before	1	98	98	3.17	0.44
GL	FM4	After	99	195	96	2.67	0.29
PR	SI1st	Before	1	54	54	0.97	0.40
PR	SI1st	After	55	151	96	1.06	0.57
GR	SI1st	Before	1	54	54	0.20	0.12
GR	SI1st	After	55	151	96	0.30	0.18
PL	SI1st	Before	1	60	60	2.02	1.56
PL	SI1st	After	61	157	96	0.49	0.25
GL	SI1st	Before	1	60	60	1.77	1.31
GL	SI1st	After	61	157	96	0.72	0.41
PR	SI3rd	Before	1	54	54	0.46	0.17
PR	SI3rd	After	55	151	96	0.53	0.26
GR	SI3rd	Before	1	54	54	0.26	0.15
GR	SI3rd	After	55	151	96	0.30	0.16
PL	SI3rd	Before	1	60	60	2.91	1.51
PL	SI3rd	After	61	157	96	0.27	0.12
GL	SI3rd	Before	1	60	60	1.27	0.77
GL	SI3rd	After	61	157	96	0.44	0.23
PR	DiffDA1	Before	1	54	54	2.50	0.55
PR	DiffDA1	After	55	151	96	2.16	0.58
GR	DiffDA1	Before	1	54	54	4.56	1.56
GR	DiffDA1	After	55	151	96	3.94	1.26
PL	DiffDA1	Before	1	60	60	17.29	3.65
PL	DiffDA1	After	61	157	96	1.99	0.42
GL	DiffDA1	Before	1	60	60	6.97	1.92
GL	DiffDA1	After	61	157	96	3.57	0.93
PR	DP2P	Before	1	54	54	12.63	2.74
PR	DP2P	After	55	151	96	11.51	3.28
GR	DP2P	Before	1	54	54	23.22	7.29
GR	DP2P	After	55	151	96	19.39	5.96
PL	DP2P	Before	1	60	60	82.22	19.63
PL	DP2P	After	61	157	96	10.48	2.62
GL	DP2P	Before	1	60	60	42.50	14.95
GL	DP2P	After	61	157	96	19.02	5.12

TABLE B.12.—TAIL NUMBER 16 STATISTICAL PARAMETERS
(a) Number 16—FPG101

Location	CI name	Status	Index start	Index end	No. points	Mean	STD
PR	DA1	Before	1	463	463	5.82	2.33
PR	DA1	After	464	606	142	22.95	8.65
GR	DA1	Before	1	463	463	6.92	2.42
GR	DA1	After	464	605	141	23.56	8.60
PL	DA1	Before	1	488	488	49.82	15.68
PL	DA1	After	489	630	141	11.78	2.41
GL	DA1	Before	1	490	490	51.07	15.10
GL	DA1	After	491	634	143	12.72	2.24
PR	FM4	Before	1	462	462	2.40	0.31
PR	FM4	After	463	604	141	3.00	0.40
GR	FM4	Before	1	462	462	2.88	0.24
GR	FM4	After	463	604	141	2.78	0.24
PL	FM4	Before	1	487	487	2.84	0.37
PL	FM4	After	488	628	140	2.91	0.24
GL	FM4	Before	1	487	487	3.27	0.36
GL	FM4	After	488	628	140	2.99	0.25
PR	SI1st	Before	1	463	463	0.79	0.32
PR	SI1st	After	464	606	142	2.46	0.90
GR	SI1st	Before	1	463	463	3.23	1.09
GR	SI1st	After	464	605	141	2.55	0.87
PL	SI1st	Before	1	488	488	2.61	1.43
PL	SI1st	After	489	630	141	1.66	0.46
GL	SI1st	Before	1	490	490	6.78	1.34
GL	SI1st	After	491	634	143	2.70	0.58
PR	SI3rd	Before	1	463	463	0.49	0.13
PR	SI3rd	After	464	606	142	1.34	0.36
GR	SI3rd	Before	1	463	463	2.25	0.54
GR	SI3rd	After	464	605	141	1.56	0.50
PL	SI3rd	Before	1	488	488	2.10	0.77
PL	SI3rd	After	489	630	141	1.07	0.19
GL	SI3rd	Before	1	490	490	4.12	0.69
GL	SI3rd	After	491	634	143	2.20	0.37
PR	DiffDA1	Before	1	463	463	3.77	0.85
PR	DiffDA1	After	464	606	142	3.92	0.73
GR	DiffDA1	Before	1	463	463	4.27	0.78
GR	DiffDA1	After	464	605	141	6.47	1.19
PL	DiffDA1	Before	1	488	488	8.97	4.12
PL	DiffDA1	After	489	630	141	4.78	0.42
GL	DiffDA1	Before	1	490	490	11.33	1.76
GL	DiffDA1	After	491	634	143	5.93	0.64
PR	DP2P	Before	1	463	463	17.76	3.27
PR	DP2P	After	464	606	142	21.86	4.78
GR	DP2P	Before	1	463	463	24.65	4.28
GR	DP2P	After	464	605	141	37.35	7.79
PL	DP2P	Before	1	488	488	48.80	21.77
PL	DP2P	After	489	630	141	26.34	3.01
GL	DP2P	Before	1	490	490	72.83	14.17
GL	DP2P	After	491	634	143	35.56	4.55

TABLE B.12.—CONCLUDED
(b) Number 16—120KTA

Location	CI name	Status	Index start	Index end	No. points	Mean	STD
PR	DA1	Before	1	142	142	14.54	3.17
PR	DA1	After	143	188	45	49.11	7.30
GR	DA1	Before	1	142	142	14.38	3.44
GR	DA1	After	143	188	45	51.06	7.38
PL	DA1	Before	1	150	150	71.62	18.30
PL	DA1	After	151	196	45	32.60	7.74
GL	DA1	Before	1	150	150	72.62	18.19
GL	DA1	After	151	196	45	33.56	7.66
PR	FM4	Before	1	142	142	2.09	0.24
PR	FM4	After	143	188	45	2.93	0.32
GR	FM4	Before	1	142	142	2.94	0.31
GR	FM4	After	143	188	45	2.91	0.16
PL	FM4	Before	1	150	150	2.87	0.34
PL	FM4	After	151	196	45	2.98	0.29
GL	FM4	Before	1	150	150	3.19	0.28
GL	FM4	After	151	196	45	3.00	0.24
PR	SI1st	Before	1	142	142	0.96	0.31
PR	SI1st	After	143	188	45	2.25	0.63
GR	SI1st	Before	1	142	142	4.55	1.06
GR	SI1st	After	143	188	45	5.35	1.32
PL	SI1st	Before	1	150	150	2.81	1.40
PL	SI1st	After	151	196	45	2.36	0.62
GL	SI1st	Before	1	150	150	5.03	1.50
GL	SI1st	After	151	196	45	3.66	0.92
PR	SI3rd	Before	1	142	142	0.61	0.12
PR	SI3rd	After	143	188	45	1.52	0.36
GR	SI3rd	Before	1	142	142	2.63	0.43
GR	SI3rd	After	143	188	45	4.08	0.62
PL	SI3rd	Before	1	150	150	2.25	0.75
PL	SI3rd	After	151	196	45	1.52	0.30
GL	SI3rd	Before	1	150	150	3.65	0.79
GL	SI3rd	After	151	196	45	3.36	0.44
PR	DiffDA1	Before	1	142	142	8.18	1.34
PR	DiffDA1	After	143	188	45	6.55	0.97
GR	DiffDA1	Before	1	142	142	5.97	1.17
GR	DiffDA1	After	143	188	45	11.75	1.09
PL	DiffDA1	Before	1	150	150	11.85	4.65
PL	DiffDA1	After	151	196	45	6.30	0.62
GL	DiffDA1	Before	1	150	150	15.23	2.77
GL	DiffDA1	After	151	196	45	8.21	0.76
PR	DP2P	Before	1	142	142	36.79	6.31
PR	DP2P	After	143	188	45	36.32	5.24
GR	DP2P	Before	1	142	142	36.39	7.38
GR	DP2P	After	143	188	45	74.24	8.64
PL	DP2P	Before	1	150	150	65.64	26.24
PL	DP2P	After	151	196	45	35.87	4.65
GL	DP2P	Before	1	150	150	103.29	24.59
GL	DP2P	After	151	196	45	52.71	5.97

TABLE B.13.—TAIL NUMBER 18 STATISTICAL PARAMETERS—FPG101

Location	CI name	Status	Index start	Index end	No. points	Mean	STD
PR	DA1	Before	1	29	29	20.86	11.61
PR	DA1	After	30	488	458	25.09	10.14
GR	DA1	Before	1	29	29	22.81	11.57
GR	DA1	After	30	488	458	27.25	10.01
PL	DA1	Before	1	29	29	24.43	4.17
PL	DA1	After	30	488	458	19.67	7.78
GL	DA1	Before	1	29	29	15.71	5.14
GL	DA1	After	30	490	460	21.20	7.97
PR	FM4	Before	1	29	29	2.84	0.31
PR	FM4	After	30	487	457	2.93	0.32
GR	FM4	Before	1	29	29	2.63	0.23
GR	FM4	After	30	485	455	2.63	0.20
PL	FM4	Before	1	29	29	4.01	0.32
PL	FM4	After	30	485	455	2.77	0.31
GL	FM4	Before	1	29	29	2.94	0.26
GL	FM4	After	30	485	455	2.86	0.24
PR	SI1st	Before	1	29	29	1.51	0.44
PR	SI1st	After	30	488	458	1.97	0.72
GR	SI1st	Before	1	29	29	2.65	0.82
GR	SI1st	After	30	488	458	2.67	1.10
PL	SI1st	Before	1	29	29	4.54	1.04
PL	SI1st	After	30	488	458	2.17	0.69
GL	SI1st	Before	1	29	29	1.51	0.62
GL	SI1st	After	30	490	460	2.66	1.03
PR	SI3rd	Before	1	29	29	0.89	0.18
PR	SI3rd	After	30	488	458	1.04	0.28
GR	SI3rd	Before	1	29	29	2.99	0.47
GR	SI3rd	After	30	488	458	3.74	0.77
PL	SI3rd	Before	1	29	29	5.23	0.92
PL	SI3rd	After	30	488	458	1.38	0.32
GL	SI3rd	Before	1	29	29	1.04	0.39
GL	SI3rd	After	30	490	460	2.43	0.82
PR	DiffDA1	Before	1	29	29	3.56	1.11
PR	DiffDA1	After	30	488	458	3.87	1.03
GR	DiffDA1	Before	1	29	29	7.27	0.98
GR	DiffDA1	After	30	488	458	8.93	1.67
PL	DiffDA1	Before	1	29	29	18.68	3.04
PL	DiffDA1	After	30	488	458	5.47	0.63
GL	DiffDA1	Before	1	29	29	4.88	0.30
GL	DiffDA1	After	30	490	460	8.06	1.25
PR	DP2P	Before	1	29	29	19.76	6.61
PR	DP2P	After	30	488	458	21.55	6.20
GR	DP2P	Before	1	29	29	40.34	5.56
GR	DP2P	After	30	488	458	49.65	9.62
PL	DP2P	Before	1	29	29	117.59	18.23
PL	DP2P	After	30	488	458	29.25	4.65
GL	DP2P	Before	1	29	29	28.36	2.73
GL	DP2P	After	30	490	460	46.08	7.39

TABLE B.14.—TAIL NUMBER 20 STATISTICAL PARAMETERS
(a) Number 20—FPG101

Location	CI name	Status	Index start	Index end	No. points	Mean	STD
PR	DA1	Before	1	492	492	28.13	24.84
PR	DA1	After	493	503	10	39.50	12.43
GR	DA1	Before	1	492	492	24.67	26.13
GR	DA1	After	493	503	10	39.31	12.55
PL	DA1	Before	1	529	529	11.52	12.01
PL	DA1	After	530	540	10	7.49	2.03
GL	DA1	Before	1	531	531	8.35	2.51
GL	DA1	After	532	542	10	9.05	1.99
PR	FM4	Before	1	492	492	2.72	0.35
PR	FM4	After	493	503	10	2.43	0.27
GR	FM4	Before	1	367	367	3.22	2.62
GR	FM4	After	368	378	10	3.18	0.51
PL	FM4	Before	1	523	523	2.62	0.38
PL	FM4	After	524	534	10	3.16	0.46
GL	FM4	Before	1	523	523	2.84	0.20
GL	FM4	After	524	534	10	2.71	0.18
PR	SI1st	Before	1	492	492	2.06	1.67
PR	SI1st	After	493	503	10	2.38	0.92
GR	SI1st	Before	1	492	492	3.21	3.37
GR	SI1st	After	493	503	10	3.35	0.53
PL	SI1st	Before	1	529	529	1.40	1.12
PL	SI1st	After	530	540	10	1.64	0.44
GL	SI1st	Before	1	531	531	1.62	1.01
GL	SI1st	After	532	542	10	2.39	1.06
PR	SI3rd	Before	1	492	492	1.40	1.06
PR	SI3rd	After	493	503	10	1.24	0.32
GR	SI3rd	Before	1	492	492	1.91	1.77
GR	SI3rd	After	493	503	10	2.80	0.44
PL	SI3rd	Before	1	529	529	0.83	0.51
PL	SI3rd	After	530	540	10	0.89	0.17
GL	SI3rd	Before	1	531	531	1.07	0.55
GL	SI3rd	After	532	542	10	1.43	0.55
PR	DiffDA1	Before	1	492	492	10.83	7.26
PR	DiffDA1	After	493	503	10	8.37	1.24
GR	DiffDA1	Before	1	492	492	5.79	2.90
GR	DiffDA1	After	493	503	10	7.64	0.92
PL	DiffDA1	Before	1	529	529	8.48	12.56
PL	DiffDA1	After	530	540	10	3.90	0.65
GL	DiffDA1	Before	1	531	531	5.37	1.17
GL	DiffDA1	After	532	542	10	6.04	0.63
PR	DP2P	Before	1	492	492	54.06	33.05
PR	DP2P	After	493	503	10	41.56	7.21
GR	DP2P	Before	1	492	492	34.14	19.06
GR	DP2P	After	493	503	10	47.80	7.67
PL	DP2P	Before	1	529	529	38.18	48.97
PL	DP2P	After	530	540	10	22.06	3.06
GL	DP2P	Before	1	531	531	30.34	6.89
GL	DP2P	After	532	542	10	32.78	4.00

TABLE B.14.—CONCLUDED
(b) Number 20—120KTA

Location	CI name	Status	Index start	Index end	No. points	Mean	STD
PR	DA1	Before	1	76	76	37.75	13.55
PR	DA1	After	N/A	N/A	N/A	N/A	N/A
GR	DA1	Before	1	76	76	37.38	13.57
GR	DA1	After	N/A	N/A	N/A	N/A	N/A
PL	DA1	Before	1	91	91	33.34	10.69
PL	DA1	After	N/A	N/A	N/A	N/A	N/A
GL	DA1	Before	1	91	91	34.28	11.35
GL	DA1	After	N/A	N/A	N/A	N/A	N/A
PR	FM4	Before	1	76	76	2.55	0.29
PR	FM4	After	N/A	N/A	N/A	N/A	N/A
GR	FM4	Before	1	76	76	3.14	0.31
GR	FM4	After	N/A	N/A	N/A	N/A	N/A
PL	FM4	Before	1	91	91	2.85	0.29
PL	FM4	After	N/A	N/A	N/A	N/A	N/A
GL	FM4	Before	1	91	91	2.87	0.26
GL	FM4	After	N/A	N/A	N/A	N/A	N/A
PR	SI1st	Before	1	76	76	2.45	1.47
PR	SI1st	After	N/A	N/A	N/A	N/A	N/A
GR	SI1st	Before	1	76	76	3.05	0.90
GR	SI1st	After	N/A	N/A	N/A	N/A	N/A
PL	SI1st	Before	1	91	91	1.94	0.69
PL	SI1st	After	N/A	N/A	N/A	N/A	N/A
GL	SI1st	Before	1	91	91	6.36	2.32
GL	SI1st	After	N/A	N/A	N/A	N/A	N/A
PR	SI3rd	Before	1	76	76	1.85	0.98
PR	SI3rd	After	N/A	N/A	N/A	N/A	N/A
GR	SI3rd	Before	1	76	76	2.00	0.62
GR	SI3rd	After	N/A	N/A	N/A	N/A	N/A
PL	SI3rd	Before	1	91	91	1.35	0.31
PL	SI3rd	After	N/A	N/A	N/A	N/A	N/A
GL	SI3rd	Before	1	91	91	3.47	0.96
GL	SI3rd	After	N/A	N/A	N/A	N/A	N/A
PR	DiffDA1	Before	1	76	76	9.83	2.63
PR	DiffDA1	After	N/A	N/A	N/A	N/A	N/A
GR	DiffDA1	Before	1	76	76	6.63	2.41
GR	DiffDA1	After	N/A	N/A	N/A	N/A	N/A
PL	DiffDA1	Before	1	91	91	7.26	1.14
PL	DiffDA1	After	N/A	N/A	N/A	N/A	N/A
GL	DiffDA1	Before	1	91	91	8.42	1.17
GL	DiffDA1	After	N/A	N/A	N/A	N/A	N/A
PR	DP2P	Before	1	76	76	49.91	15.31
PR	DP2P	After	N/A	N/A	N/A	N/A	N/A
GR	DP2P	Before	1	76	76	43.39	15.99
GR	DP2P	After	N/A	N/A	N/A	N/A	N/A
PL	DP2P	Before	1	91	91	39.89	7.02
PL	DP2P	After	N/A	N/A	N/A	N/A	N/A
GL	DP2P	Before	1	91	91	52.79	9.74
GL	DP2P	After	N/A	N/A	N/A	N/A	N/A

Appendix C.—CI Comparison for Damaged and Undamaged Cases

C.1 Output Gear Comparisons

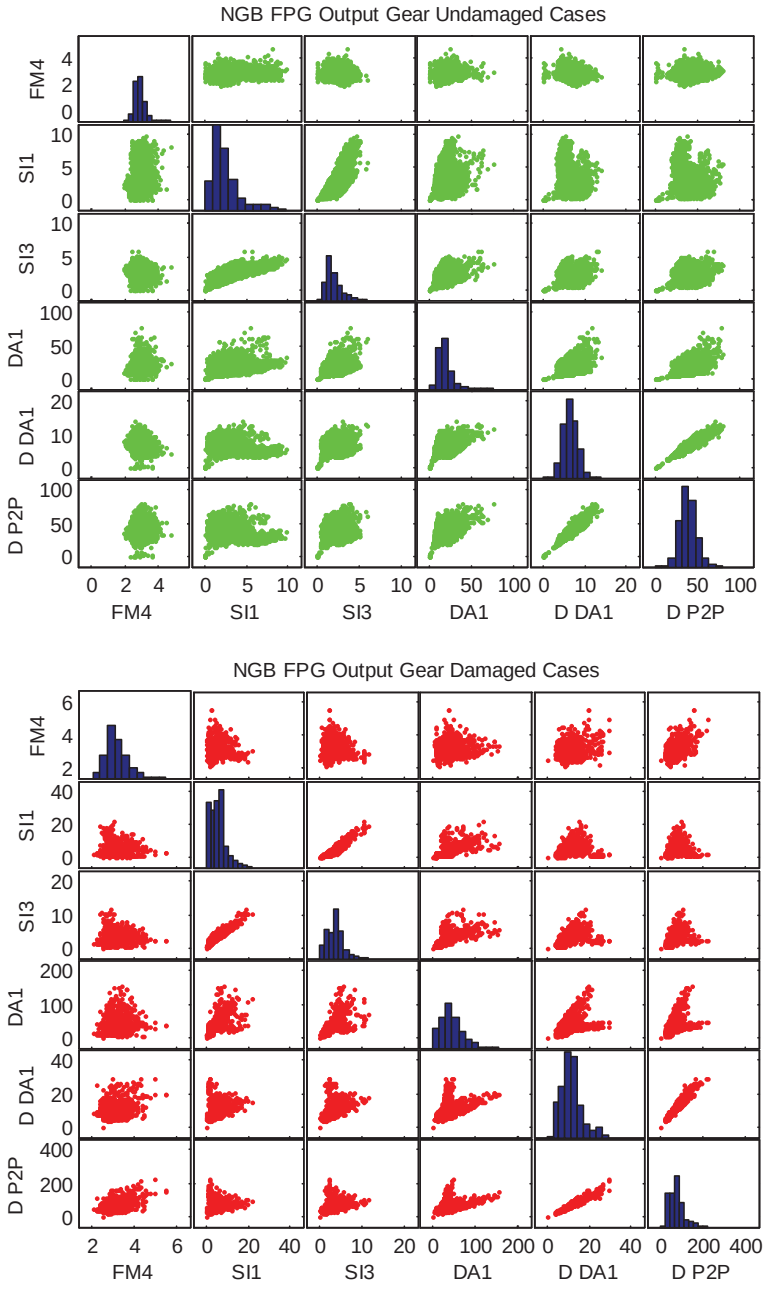

Figure C.1.1.—Output Gear CI Comparison for FPG Regime

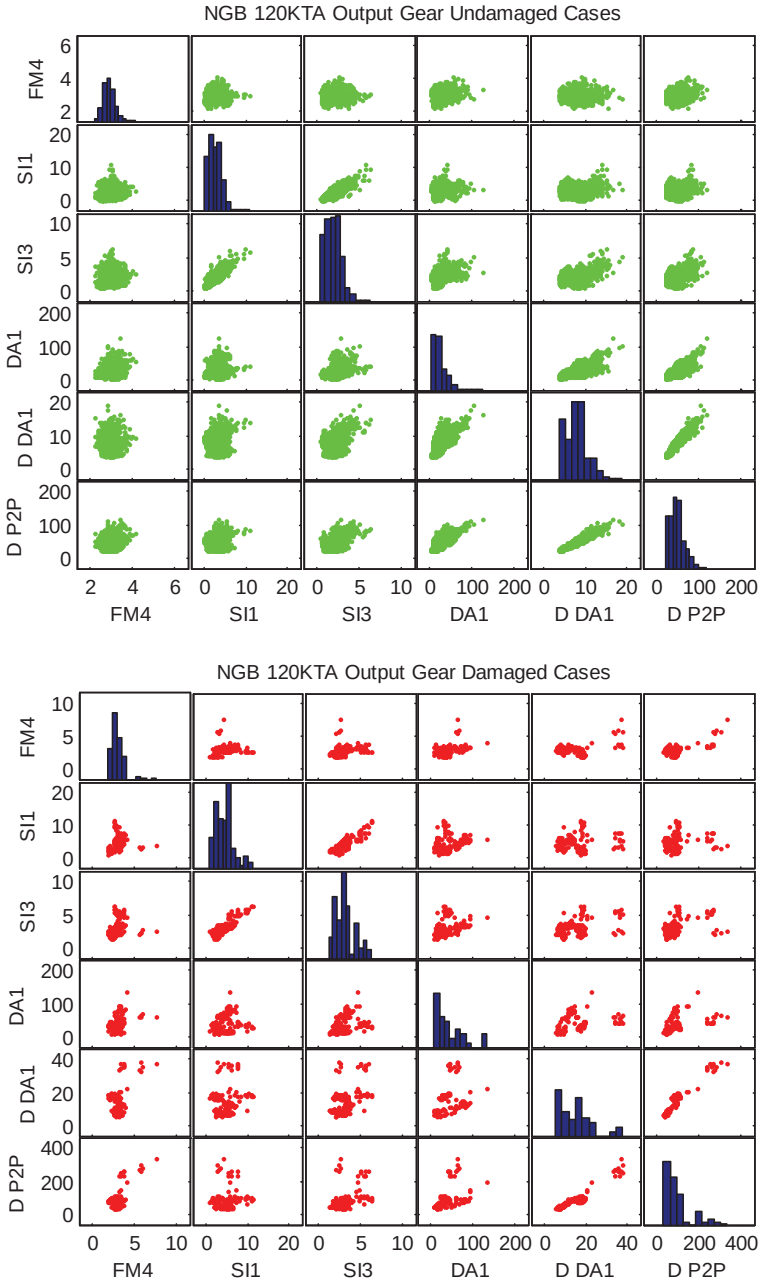

Figure C.1.2.—Output Gear CI Comparison for 120KTA Regime

C.2 Input Pinion Comparisons

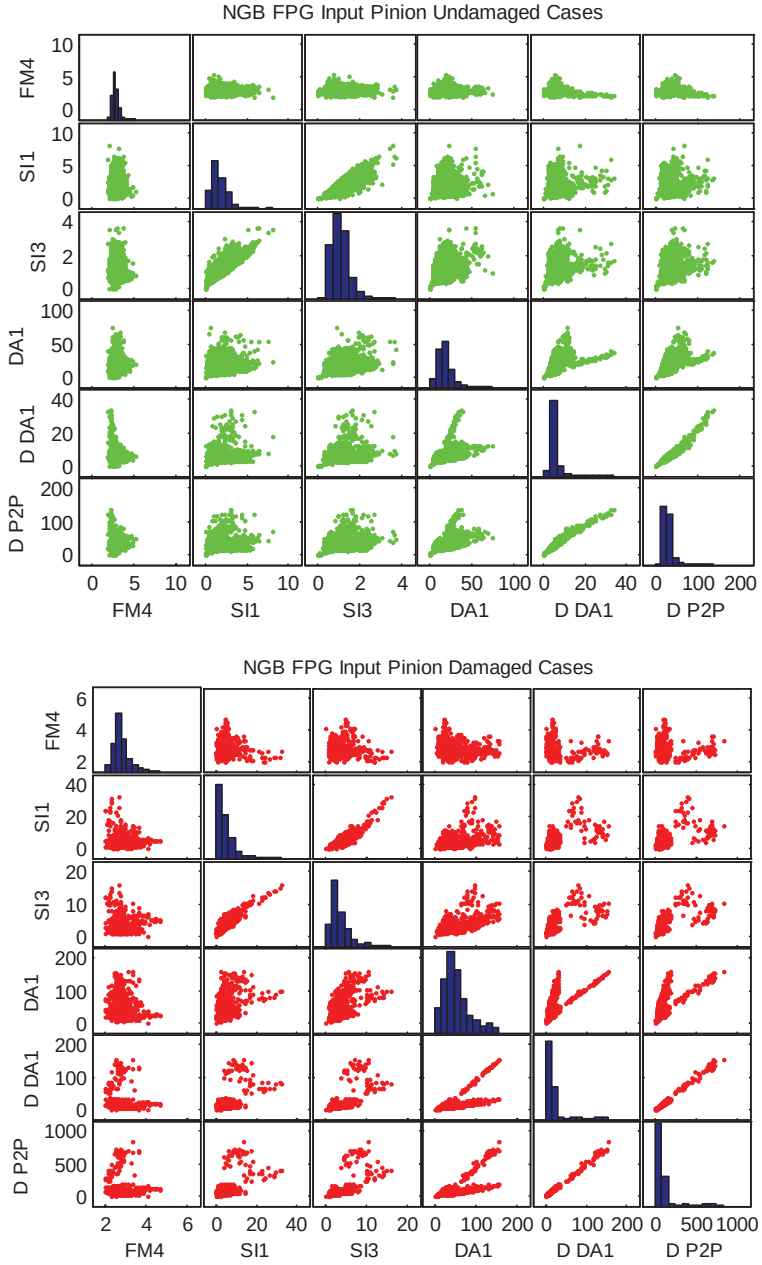

Figure C.2.1.—Input Pinion CI Comparison for FPG Regime

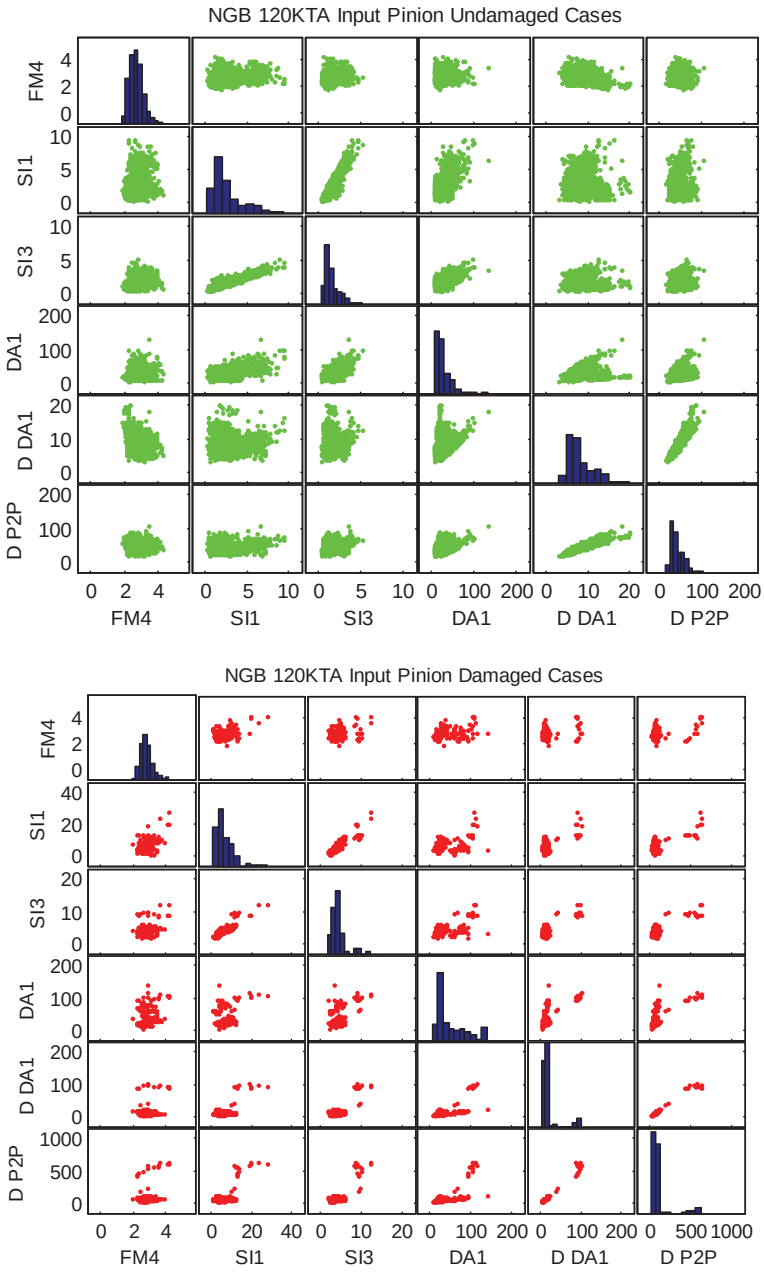

Figure C.2.2.—Input Pinion CI Comparison for 120KTA Regime

References

1. Federal Aviation Administration Advisory Circular (AC) 29–2C, Section MG–15, Airworthiness Approval of RC (HUMS) per Code of Federal Regulations, Title 14-Aeronautics and Space, Chapter I-Federal Aviation Administration, Department of Transportation, Part 29-Airworthiness Standards: Transport Category Rotorcraft.
2. Antolick, L., Wade, D.R. and Brower, N.G.: "Application of Advanced Vibration Techniques for Enhancing Bearing Diagnostics on a HUMS-Equipped Fleet," Presented at the American Helicopter Society CBM Specialists Conference, Huntsville, AL, February 11-13 2013.
3. Civil Aviation Authority: CAP 753, "Helicopter Vibration Health Monitoring (VHM) Guidance Material for Operators Utilizing VHM in Rotor and Rotor Drive Systems of Helicopters," First Edition June 2006. First Edition incorporating amendment 2012/01, August 2012.
4. Delgado, I., Dempsey, P., Antolick, L. and Wade, D.: "Continued Evaluation of Gear Condition Indicator Performance on Rotorcraft Fleet," Airworthiness, CBM, and HUMS Specialists' Meeting, February 11-13, 2013, Huntsville, AL.
5. Antolick, L., Branning, J., Dempsey, P. and Wade, D.: "Evaluation of Gear Condition Indicator Performance on Rotorcraft Fleet," American Helicopter Society International 66th Annual Forum 2010, Phoenix, AZ, 11-13 May 2010.
6. Dempsey, P.J. and Brandon, E.B.: "Validation of Helicopter Gear Condition Indicators Using Seeded Fault Tests," MFPT 2013 Conference, May 13-17, 2013, Cleveland, OH. NASA/TM—2013-217872.
7. Dempsey, P.J.: "Investigation of Spiral Bevel Gear Condition Indicator Validation Via AC–29–2C Using Test Rig Damage Progression Test Data," NASA/TM—2014-218384, September 2014.
8. U.S. Army Aeronautical Design Standard for Condition Based Maintenance, ADS79 Handbook. August 2012.
9. Wade, D., and Larsen, C., Roth, R., and Shelley, S., "Final Report of Bearing Condition Indicator Refinement Project," Technical Report Rdmr Ae-06-01, June 2011.
10. Massey, F. J. "The Kolmogorov-Smirnov Test for Goodness of Fit," Journal of the American Statistical Association. Vol. 46, No. 253, 1951, pp. 68–78.
11. Islam, A., Demspey, P., Feldman, J. and Larsen, C., "Characterization and Comparison of Vibration Transfer Paths in a Helicopter Gearbox and a Fixture Mounted Gearbox," NASA/TM—2013-216586, September 2013.
12. ANSI/AGMA 1010-E95. Appearance of Gear Teeth – Terminology of Wear and Failure.
13. Davies, D.P., Jenkins, S.L. and Belben, F.R.: "Survey of fatigue failures in helicopter components and some lessons learned," Engineering Failure Analysis 32 (2013) 134–151.
14. Department of the Army Pamphlet (DA PAM) 738-751 "Functional User's Manual for the Army Maintenance Management System – Aviation."
15. Stewart, R.M. "Some useful data analysis techniques for gearbox diagnostics. Machine Health Monitoring Group, Institute of Sound and Vibration Research," University of Southampton, Report MHM/R/10/77, July 1977.
16. Zakrajsek, J.J. 1989. An investigation of gear mesh failure prediction techniques. NASA TM–102340, AVSCOM TM 89–C-005.
17. Zakrajsek, J.J., Handschuh, R.F., and Decker, H.J. 1994. "Application of fault detection techniques to spiral bevel gear fatigue data," Proceedings of the 48th Meeting of the Mechanical Failures Prevention Group. Office of Naval Research, Arlington, VA, pp. 93–104.
18. Keller, J.A., "A Dictionary of Terms for Machinery Diagnostics of Gearboxes," U.S. Army RDECOM, Aviation Engineering Directorate Aeromechanics Division, Redstone Arsenal, AL.
19. Mimnagh, M.L. and Neubert, C.G., "SH-60 Helicopter Intermediate Gearbox Gear Tooth Failure Diagnostic Test Results," Interim Report, Naval Air Systems Command Headquarters, Arlington VA, August 6, 1997.
20. Triola, Mario. Elementary Statistics. 6th edition. Addison-Wesley 1995.