ABSTRACT
After a series of unresolved bearing failures and friction anomalies on spacecraft utilizing ITHACO reaction wheels, a Relentless Root Cause Analysis completed by United Technologies Corporation led to unexpected conclusions which implicated the space charging environment as a likely root cause, and which had not been considered in many previous failure investigations. A strong correlation of the space charging environment with a statistically significant number of friction events observed on-orbit was supported by the results of laboratory tests which successfully duplicated the friction event signatures. Countermeasures were developed to minimize the occurrence of friction events and to increase the probability of successful recovery from anomalous friction increases. This phenomenology likely has applications beyond reaction wheels and should be considered for all past and future mechanisms using ball bearings.

1. INTRODUCTION
Reaction Wheel Assembly (RWA) bearing friction anomalies and failures have plagued many missions since the dawn of the space age. The ITHACO RWA product line, which was purchased by United Technologies Corporation (UTC) as part of the acquisition of Goodrich in 2012, had systemic failures on a number of spacecraft, including NASA’s Far Ultraviolet Spectroscopic Explorer (FUSE), and most recently on the Kepler space telescope. A series of failure investigations performed over a decade ultimately failed to successfully determine root cause. A Relentless Root Cause Analysis (RRCA) was initiated by UTC in 2011 when anomalous friction behaviour continued to be observed on-orbit. After 5 years of testing and analysis, it was eventually concluded that the bearing failures and anomalies were in response to the environment, and likely caused by electrical discharge across the bearings due to rapid spacecraft charging in a volatile space plasma environment. These conclusions are based on statistical correlations of failures and friction events to significant geomagnetic storms combined with the results of testing which duplicated the friction behaviour by simply applying a modest voltage across RWA bearings.

2. REACTION WHEEL FAILURE HISTORY
The ITHACO RWA product line was developed starting in 1988, with launches beginning in 1994. The first RWA failure occurred on the FUSE Spacecraft on November 25, 2001, followed by the failure of a second RWA just two weeks later. The spacecraft was successfully reconfigured to operate and acquire science with the remaining two wheels, as described in [1], until a third RWA failed in December 2004. It is quite remarkable that the spacecraft was again reconfigured to operate with a single RWA as described in [2], and then continued acquiring science until the last remaining RWA failed in April of 2007.

The Kepler Spacecraft was launched in a Heliocentric Earth trailing orbit on March 7, 2009, and experienced failures of two RWAs in 2012 and 2013. The attitude control system was reconfigured to use the two remaining wheels in an alternate mission identified as K2, and the remaining two RWAs have been operating for over 8 years without incident.

There have been additional ITHACO RWA failures and friction anomalies which are also supported by the conclusions of this paper, but only the aforementioned will be discussed and used to draw the statistical conclusions.

3. ANOMALOUS FRICTION SIGNATURES
An RWA is deemed to be failed when the bearing friction exceeds the torque authority of the motor. This is a rare, but very unfortunate, state. Anomalous bearing friction increases are more common, and have been observed when trending the health of RWAs. In most cases the anomalous friction eventually recovered to normal levels.

Most of the observed friction anomalies can be clearly segregated into dry friction (Coulomb friction) or wet friction (Newtonian viscous friction). The magnitude of a dry friction increase is independent of wheel speed, and therefore remains present while crossing zero speed. This is a characteristic of rubbing friction between two surfaces under load. Viscous friction increase is...
proportional to wheel speed, with no change exhibited at zero speed, which is typically a response to shearing of a fluid between two surfaces moving relative to each other. The characteristic signatures of both of these types of friction anomalies are discussed in detail in [3], and represented graphically in Fig. 1. It is typical for a dry friction increase to occur gradually over a period of a few days and then stabilize at the elevated friction level, while the viscous friction increase is instantaneous.

Figure 1. Dry and Wet Friction Increase Signatures

Dry friction is typically characterized by a 1-2 mN-m increase in friction which is independent of speed. The most likely mechanism for this signature is retainer windup combined with a roughened surface finish on the balls. Retainer windup occurs when sufficient asymmetry is present in the bearing raceway to result in ball speed variation exceeding the ball pocket clearance. This results in binding of the retainer and rubbing in the ball pockets and between the retainer pilot diameter and outer race guiding land, as shown in Fig. 2. In laboratory tests, the increased friction could not be duplicated by retainer windup alone, so it is hypothesized that the increased roughness of the balls rubbing in the ball pockets is necessary for the friction to increase. This type of friction increase usually returns to normal, and increased operating speeds have been shown to increase the chance of recovery.

Figure 2. Retainer Windup Rubbing Points due to excessive ball speed variation

The wet friction increase is a rarer event, and is believed to be due to a change in ball control from inner race control to outer race control, due to an instantaneous increase in the roughness of the outer raceway.

4. RELENTLESS ROOT CAUSE ANALYSIS

Root Cause Analysis for friction anomalies on FUSE was performed in 2001. The dry friction increase signature, which usually results from rubbing between two surfaces, and the systemic recovery from friction anomalies initially led to exoneration of the bearings, and suggested mechanical contact between the flywheel and housing, as presented in [4]. A similar friction increase on a spacecraft in 2007 debunked that hypothesis, since the anomalous RWA had incorporated design modifications which increased suspected clearances, thus implicating the bearings. An extensive root cause analysis was performed with no confirmed conclusions, resulting in several design modifications to the suspension system to reduce risk of reoccurrence. In March of 2011, the failure of an RWA with the design modifications reopened the root cause analysis.

United Technologies, after their recent acquisition of Goodrich Corporation which included the ITHACO RWA product line, embarked on an RRCA to resolve the RWA failures and anomalies. A rigorous test program accompanied detailed modelling and analysis of every aspect of the RWA design. A total of 36 initially credible items were positively eliminated from the fault tree by test, inspection or analysis, including many previously eliminated items which were revisited and eliminated with fresh objective evidence.

Ten dedicated RWAs were built and utilized in over 75 controlled tests. The key scenarios which were investigated were bearing alignment, preload, contamination, and anomalous raceway wear observed during the bearing run-in process. These scenarios were completely exonerated by the results of the testing, with the exception of bearing wear during the run-in process. This initiated a series of controlled tests to determine the variables that could affect the anomalous wear.

Test bearings were lubricated with a controlled amount of free oil supplemented by a charge of grease. With the standard lubrication process, the bearing inner race wear depth was consistently 0.3 to 0.4 microns, regardless of how the grease was initially distributed. When identical tests were run with only oil, the bearings showed an increase in wear depth when marginally lubricated with oil, and when completely flooded with oil. These contradicting results led to a conclusion that the rheological lubricant properties were not affecting the wear, since the oil is more mobile than any oil/grease mixture, and which should tend to reduce any lubricant starvation effects. This resulted in the introduction of electrical discharge as a new branch of the fault tree. While electrical discharge is a common problem in terrestrial high voltage motors, as discussed in [5], it could not be found in any searches of published aerospace mechanism failure analyses.
It was observed that the RWA motor induces a voltage of 1 to 2 volts into the rotor when operating in EHD (Elasto Hydro Dynamic) isolation. For the synthetic hydrocarbon lubricant used in the bearings, the breakdown voltage constant was measured to be 45 kV/mm. This translates to a breakdown at a lubricant film thickness of 0.02 microns (~1 micro-inch) at 1 volt differential across the bearings. It was surmised that electrical discharge erosion during the bearing run-in process was the cause for the systemic wear, similar to the mechanism of Electrical Discharge Machining.

Results of additional tests led to an hypothesis that spacecraft chassis voltage fluctuations could affect electrical discharge across the bearings at higher voltages than the 1 to 2 volts induced by the motor. Strong correlations of the dates of RWA failures with geomagnetic storms substantiated the hypothesis and led to additional tests which applied as low as 6 Volts across RWA bearings and resulted in anomalous friction signatures and increased raceway wear. This allowed the RRCA to finally be concluded in March of 2016.

RRCA Statistics: Duration of RRCA: 4+ years
Test RWAs manufactured: 10
RWA tests completed: 75
Bearings Tested and Inspected: 150

5. CORRELATIONS WITH SPACE WEATHER

The most significant breakthrough of the RRCA was when a strong correlation was made between RWA bearing failures/anomalies and space weather, specifically Coronal Mass Ejections (CME) from the Sun, and the resulting geomagnetic storms. In addition, there were a number of failures or anomalies on different spacecraft which occurred during the same geomagnetic storm. While the correlation is strong on all reviewed failures and anomalies, the statistical arguments for this paper will only take into account the failures and anomalies on two NASA spacecraft, namely FUSE and Kepler.

It is important to note that correlation does not prove causation. In the case of the space plasma environment and mechanisms there are no known parallel or related potential causes other than the potential effects of space charging. We therefore reserve the conclusion regarding space charging as a likely cause, and only conclude the root cause is related to the space environment.

5.1 FUSE Spacecraft Friction Event Correlation

Failures of all of the RWAs on FUSE were preceded by dry friction anomalies, which recovered to normal levels after operating at high speed (2000 rpm or more) for a period of days or hours. The date of the initiation of the friction increase was taken from the trending data.

A list of the prominent FUSE anomalies and failures is presented in Tab. 1, with Ap index, the ranking of any geomagnetic storm within the 3 days leading up to the observed friction increase, and whether the friction recovered to normal after operating at high speed.

<table>
<thead>
<tr>
<th>Observed Friction Increase</th>
<th>Friction Initiation Date</th>
<th>Ap Index</th>
<th>Geomagnetic Storm Ranking since 1994</th>
<th>Recovery after high speed operation?</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 mN-m</td>
<td>13 Feb 2001</td>
<td>26</td>
<td>Not ranked</td>
<td>Yes</td>
</tr>
<tr>
<td>700 mN-m</td>
<td>25 Nov 2001</td>
<td>104</td>
<td>20&quot;</td>
<td>No, failed RW</td>
</tr>
<tr>
<td>3 mN-m</td>
<td>15 July 2000</td>
<td>164</td>
<td>5&quot;</td>
<td>Yes</td>
</tr>
<tr>
<td>2 mN-m</td>
<td>27 July 2000</td>
<td>19</td>
<td>Not ranked</td>
<td>Yes</td>
</tr>
<tr>
<td>5 mN-m</td>
<td>3 July 2000</td>
<td>27</td>
<td>Not ranked</td>
<td>Yes</td>
</tr>
<tr>
<td>4 mN-m</td>
<td>5 Oct 2000</td>
<td>116</td>
<td>10&quot;</td>
<td>Yes</td>
</tr>
<tr>
<td>1.2 mN-m</td>
<td>25 Nov 2001</td>
<td>104</td>
<td>20&quot;</td>
<td>No attempt</td>
</tr>
<tr>
<td>1400 mN-m</td>
<td>10 Dec 2001</td>
<td>3</td>
<td>Failed after operating at low speed for 15 days in elevated friction state.</td>
<td></td>
</tr>
<tr>
<td>5 mN-m</td>
<td>12 Sept 2002</td>
<td>14</td>
<td>Not ranked</td>
<td>Yes</td>
</tr>
<tr>
<td>&gt;40 mN-m</td>
<td>Dec 2004</td>
<td>N/A</td>
<td>N/A</td>
<td>No, failed RW</td>
</tr>
<tr>
<td>RW-X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 mN-m</td>
<td>30 April 2007</td>
<td>15</td>
<td>Not ranked</td>
<td>Yes</td>
</tr>
<tr>
<td>&gt;40 mN-m</td>
<td>12 July 2007</td>
<td>21</td>
<td>Not ranked</td>
<td>No, failed RW</td>
</tr>
</tbody>
</table>

The failure of RW-X on November 25, 2001 occurred on the same day that a dry friction increase was observed on RW-Y, which remained in the elevated friction state until it failed 15 days later. Of the 12 prominent events observed, 4 occurred shortly after or during geomagnetic storms ranked in the top 20 of severity since 1994. The rarity of these events creates a strong statistical correlation, since there are only 60 days (20 storms x 3 days per storm) in the last 22 years which are in this category.

The probability of four out of the 12 events occurring on these days \( P_e \) can be determined by the binomial probability formula shown as Eq. 1.

\[
P_e = \frac{n!}{(x)!\times(n-x)!} \times P_b^x \times (1-P_b)^{(n-x)} \tag{1}
\]

where:
- \( P_e \) is the probability of the combined outcome
- \( n \) is the total number of events (12)
- \( x \) is the number of events in the category (4)
- \( P_b \) is the probability of any of these events randomly occurring on one of the days in the category as shown by Eq. 2.

\[
P_b = \frac{60\text{days}}{22\text{years} \times 365\text{days/year}} \times 100\% = 0.7\% \tag{2}
\]

The probability of four events occurring randomly on the days of the rare geomagnetic storms \( P_e \) is computed from Eq. 1 to be 0.00015%, or a 1 in 688,000 chance. The probability of correlation \( P_e \) is then given by Eq. 3.

\[
P_e = (1 - P_e) \times 100\% = 99.99998\% \tag{3}
\]
It is therefore nearly only a one in a million chance that the events and the geomagnetic storms are only related randomly, or nearly 100% certainty that there is a correlation. This strong correlation has also been confirmed in larger data sets of ITHACO RWA friction anomalies and failures, and a significant number of additional simultaneous anomalies on different spacecraft have also been observed.

5.2 Kepler Spacecraft CME Correlation

The first RWA failure on the Kepler Space Telescope occurred on July 14, 2012, during the 41st largest geomagnetic storm since 1994. A large friction increase occurred on RW2 at approximately 03:00 UT (Universal Time), as shown in Fig. 3, and a CME impact on the Earth was observed at 17:00 UT. Since the friction increase preceded the CME impact on Earth by 14 hours, it was initially assumed that there was no connection between the two events.

Subsequent analysis in 2016 revealed that the actual path of the CME reached Kepler before it arrived at Earth, and that is was very likely that the CME shock front was simultaneous with the friction increase observed on RW2. This was deduced from two references which analysed the timing of the July 12 CME. The direction of the CME was determined from observations in [6] to be 21.5 degrees from Earth, and Kepler just happened to be trailing Earth orbit by 21.5 degrees, so the CME was directed squarely at Kepler. The average velocity of the CME as it approached Earth was estimated in Ref. [6] to be 650 km/s. With this assumption and using the SSEF (Self-Similar Expansion Fitting) modelling of Ref. [6] with an assumed half width of 40 degrees overlaid with the MHD (Magneto-Hydro-Dynamic) three dimensional modelling of [7], the expected arrival time at Kepler is approximately 14 hours before arrival at Earth as shown in Fig. 4. From this it is concluded that that it is not only possible, but likely, that the CME shock front impacting Kepler was simultaneous with the abrupt friction increase observed on RW2. At a CME velocity of 65 km/sec, the 4.7 meter spacecraft would have been enveloped by the CME shock wave-front in 7 μsec, which would result in a very high rate of charging of the spacecraft chassis, and which strongly supports the space charging hypothesis.

6. ELECTRICAL DISCHARGE FAILURE MECHANISM

While the mechanism of electrical discharge across a bearing is simple physics, the sequence of events necessary to trigger friction increase and ultimately bearing failure is extremely complex, as shown in the flow chart presented in Fig. 5. The most significant variables are the lubricant electrical properties (resistivity, dielectric constant, dielectric breakdown coefficient), the lubricant film thickness and the rate of change of the spacecraft chassis voltage in a volatile space plasma environment ($dV/dt$). All of these key variables are moving targets which complicates things even further. The lubricant electrical properties have been shown to evolve over weeks, months or years of operating time, the EHD film thickness changes with wheel speed, and the rate of change of spacecraft charging changes with the weather.
6.1 Lubricant Electrical Property Evolution

The combination of the first two blocks of the flow chart in Fig. 5 depict some initial conditioning of the bearings by electrical discharge as a result of the 1 to 2 volts induced into the rotor by the motor, and the operation during bearing run-in and on-orbit. This results in evolution of the lubricant composition which increases the bearing electrical resistance and breakdown voltage. It was observed in tests that the resistance across the bearings at 1000 rpm increased from 5 MΩ to 60 MΩ over the course of 100 hours of bearing run-in at 65°C, and that the breakdown voltage also increased.

The electrical properties of the bearing lubricant were measured by United Technologies Research Center (UTRC), as presented in Fig. 6. Samples of four different compositions were tested. The most surprising result was a nearly two-order-of-magnitude increase in the lubricant resistivity without the grease thickener. This led to the realization that the evolution of the lubricant distribution during extended operation could affect the bearing resistance as the grease filler migrated off the ball track.

Figure 5. Flow chart of ED Failure Mechanism

Figure 6. Lubricant Electrical Properties by Composition

Figure 7. Friction Anomaly Occurrences by Revolutions for a sample of 61 Type B RWAs over the time period from 2000 to 2015
6.2 EHD Film Thickness

A lubricant film is necessary for any electrical discharge to occur, since the bearing resistance is effectively a short circuit when operating sub-EHD. Reference [8] includes EHD lubricant film thickness measurements for a 6mm bore bearing using oil similar to what is used in the reaction wheels discussed herein, which show an EHD film established above 500 rpm. Test data at 3000 rpm yielded a full film thickness of 0.38 µm (7 µin), which can be extrapolated to a minimum film thickness of 0.11 µm (2.6 µin) at the inner race. Assuming the measured breakdown voltage coefficient of the oil with PbNp of 60 KV/mm from Fig. 6, this film thickness would predict a breakdown with a voltage of 6.6 V. A measurement at 3000 rpm on a test RWA which had been well run-in yielded a breakdown voltage of 23 V. This supports the argument that conditioning of the bearings with extended operating time is an important element of the failure mechanism by increasing the potential damage when higher voltages are generated across the bearings on-orbit during periods of volatile space weather.

The lubricant film thickness is proportional to the electrical resistance across the bearings and the breakdown voltage, and inversely proportional to the capacitance. Thus, wheel speed plays an important role in setting up the conditions for an electrical discharge.

6.3 Volatile Space Charging Environment

The strong correlations of reaction wheel friction events with geomagnetic storms lead to the conclusion that a volatile space charging environment is a necessary element for the assumed role of an ED event in the failure mechanism. The assumption is that the spacecraft must be charging at a rate sufficient to exceed the bleed rate across the bearing electrical resistance, resulting in a potential difference across the bearing. If this potential exceeds the breakdown voltage, an electrical discharge event will occur. Ungrounded metal is typically discouraged in spaceflight hardware to avoid this, but rotating mechanisms have typically been left ungrounded when operating on an EHD lubricant film. Rapid charging events affecting the potential of the entire spacecraft chassis are not uncommon on spacecraft, and the electrical system is typically protected by filters and a common floating ground.

In addition to the rate of spacecraft charging (i.e. \(dV/dt\)), it is also possible that the duration of the charging event could be a factor. If the charging rate is continued at a high-enough rate beyond when the voltage breakdown occurs, a period of sustained arcing across the lubricant film could be maintained for some duration, resulting in a higher level of surface damage.

6.4 Surface Roughening due to ED in Bearing

Electrical discharge across the bearing lubricant film at sufficiently high voltages results in crater formation. An example of the results of a discharge from ball to race is shown in Fig. 8, which also presents the inevitable hardness increase of the rim of the formed crater, since the molten race material will be instantly oil quenched by the lubricant in the bearing, resulting in formation of untempered Martensite with a hardness as high as Rockwell C65, compared to the tempered hardnesses of C58 and C60 for the race and ball, respectively. The rim of the crater increases the roughness and the higher hardness increases the abrasive properties of the raised bearing surfaces. The initial area of discharge will be more susceptible for subsequent discharges since it will be a locally smaller gap, which could tend to make cumulative discharges result in an asymmetric surface finish on the bearing race, which can result in ball speed variation and cage windup.

![Figure 8. Mechanism for rougher and more abrasive ball surface by ED from ball to race](image_url)

An alternate mechanism for increasing the roughness and hardness of a ball is shown in Fig. 9. In this case, the molten race material welds itself to the ball during the same type of electrical discharge event, resulting in hard Martensite asperities on the surface of the ball. In both of these examples, the ED can be just as likely directed from the race to the ball.
6.5 Ball Speed Variation, Cage Windup and Failure

The asymmetric surface roughness of the raceway is assumed to cause retainer windup, as discussed in Section 3.0 and shown in Fig. 2. The increased roughness of the balls is assumed to cause an anomalous Coulomb friction increase. Wear of the retainer eventually occurs in this condition when lubricant is driven from the rubbing surfaces. When the retainer wears sufficiently to fracture, the bearing is irreversibly failed since the retainer can no longer separate the balls and ball speed variation increases. Retainer fragments then seize the bearing with increased binding friction.

7. ELECTRICAL DISCHARGE TESTING

The hypothesis for ED was initially tested by applying a trapezoidal waveform with ±10V amplitude and a dV/dt of 2V/µs and a period of 100 msec across the bearings of two RWAs operating at 2000 rpm, which were pre-conditioned with 100 hours of bearing run-in. The test specimens did not demonstrate any anomalous friction increases and the bearings did not show any significant increase in wear relative to control samples.

A subsequent test, identified as Trial 9B, was run with the intention of accelerating the evolution of the lubricant resistance due to extended run-in by using only oil in the bearings, with no grease filler. The grease filler was observed to significantly reduce the lubricant electrical resistance as shown in Fig. 6. The results of the first unit showed an immediate progression of anomalous friction increase over 24 hours as shown in Fig. 11, followed by a gradual recovery to the baseline value. The second unit had a similar friction increase and also exhibited a dramatic 20 mN-m friction spike just 28 minutes after only ±6V was applied across the bearings.

Figure 11. Anomalous friction increase exhibited with ±10 applied across bearings

The bearings from the two RWAs in Trial 9B were inspected, and the visual appearance was markedly different than bearings removed from a previous test identified as Trial 5, which also used only oil as the bearing lubricant, but without any voltage applied across the bearings. The balls had a frosty appearance and the lubricant was darkened, as shown in Figure 12. The cleaned retainers exhibited unusual staining, primarily in the area of the rubbing points in the ball pockets and on the pilot diameter, as shown in Figure 13. The wear depth of the raceways was deeper in the bearings with the voltage applied, compared to the Trial 5 bearings, as shown in Figure 14. These differences are direct evidence that the voltage across the bearings affected the friction and wear in the bearing.
8. COUNTERMEASURES

Since 2010, 72 ITHACO RWAs with hybrid bearings with ceramic balls have been launched and all have operated without any known anomalous friction events. It is likely that this is due to the non-conductive property of the ceramic ball which makes the bearing immune to ED.

For steel bearings, low speeds may reduce the risk of friction increases due to lower voltage ED with thinner lubricant films during volatile space weather.

In the event increased friction is observed, operation at higher than normal speeds for a period of hours has resulted in recovery to normal friction levels and extended lifetime in a number of RWAs.

9. CONCLUSIONS

The anomalous friction increases and failures of ITHACO RWAs on the FUSE, Kepler and other spacecraft are the result of the space environment, and likely space charging. This is based on strong statistical correlation of events with geomagnetic storms, and simultaneity of events on different RWAs during geomagnetic storms. Duplication of friction events in the laboratory by applying small voltages across the rotating bearings supports this conclusion. Finally all metal ball bearing control wheels for satellites may be similarly impacted as discussed, when operated in these adverse space weather conditions.

REFERENCES