Introduction

Launched 29 September 2011, *Tiangong-1* served as China's first space station. It hosted visits from an uncrewed *Shenzhou-8* in November 2011, followed by 3-person crews aboard *Shenzhou-9* in June 2012 and *Shenzhou-10* in June 2013. On 21 March 2016, China's Space Engineering Office announced ground communications with *Tiangong-1* had been lost.\(^1\) Figure 1's *Tiangong-1* apsis height history plot corroborates an absence of control capability starting in 2016.\(^2\) Sudden apsis height increases from propulsive reboost, offsetting intervening intervals of apsis height decay from atmospheric drag, cease after December 2015.

![Diagram of *Tiangong-1* apogee height and perigee height as functions of time](image)

**Figure 1.** As-flown apogee height (green) and perigee height (red) are plotted as functions of time for *Tiangong-1* from its day of launch until its atmospheric entry and incineration circa 2.0 April 2018 UT.


\(^2\) The source of Figure 1 apsis values and all as-flown *Tiangong-1* trajectory data analyzed in this paper is [https://www.space-track.org/auth/login](https://www.space-track.org/auth/login) (accessed 1 April 2018). In narrative herein, this source is referred to as "Space-Track.org".
This paper describes methodology applied to predicting Tiangong-1’s entry date on a weekly cycle starting in September 2017. Results from this analysis are also documented.

Methodology

Three times are fundamental to Tiangong-1 entry predictions. The first two times, \( t_0 \) and \( t_1 \), define begin and end points, respectively, of a trajectory arc. The \( i \)th arc in this analysis is associated with an effective area \( A_i \) for Tiangong-1’s atmospheric drag acceleration \( \ddot{r}_D \) during that time interval. In all but the final week of Tiangong-1’s orbit lifetime, \( t_1 - t_0 \) is selected from available Space-Track.org two-line element sets (TLEs) to be within a few hours of 7 days. The following parameters are relevant to modeling \( \ddot{r}_D \).

\[
\begin{align*}
C_D & \equiv \text{Tiangong-1 coefficient of drag (valued at 2.0 throughout this analysis)} \\
m & \equiv \text{Tiangong-1 mass} = 8506 \text{ kg (reference Footnote 1)} \\
\rho & \equiv \text{atmospheric density at Tiangong-1 geocentric position} \\
v & \equiv \text{Tiangong-1 velocity relative to an Earth-fixed coordinate system (note \( v \) is the magnitude of \( v \)),}
\end{align*}
\]

Equation 1 computes \( \ddot{r}_D \), assumed to be the only sensed acceleration when simulating Tiangong-1 coasted orbit motion.

\[
\ddot{r}_D = -\frac{C_D}{2m} \rho A_i v v
\]  

After a value for \( A_i \) is developed over the \( i \)th \( t_0 \) to \( t_1 \) arc, it is used with all previous \( A_i \) values to refine a running mean value \( \bar{A} \). Coasts are then initiated at \( t_1 \) (also termed the "anchor" epoch in this analysis) with \( \bar{A} \) replacing \( A_i \) in Equation 1. These coasts terminate at the third time, atmospheric entry interface \( t_{EI} \), when Tiangong-1 simulated geodetic altitude first falls below +121.92 km.

Arguably the most unpredictable parameter in Equation 1 is \( \rho \). This analysis uses a Jacchia-Lineberry dynamic atmosphere [1] to model \( \rho \). In approximating atmospheric heating variations, dynamic atmosphere models typically use empirical measurements expressed as solar flux \( F_{10.7} \) and geomagnetic index \( A_P \). For this analysis, the current month's \( F_{10.7} \) and \( A_P \) values, as last posted before \( t_1 \) to https://sail.msfc.nasa.gov/current_solar_report/CurF10.txt (accessed 2 April 2018), are used to develop the corresponding \( A_i \), refine \( \bar{A} \), and perform coasts to \( t_{EI} \).

An attempt to quantify uncertainties in \( \rho \) modeling is made by coasting 3 times to \( t_{EI} \) for a particular \( \bar{A} \) update. Each coast is made with the Jacchia-Lineberry atmosphere configured using distinct \( (F_{10.7}, A_P) \) values available for download at sail.msfc. The 95% atmosphere's \( (F_{10.7}, A_P) \) values are relatively large and considered to produce 2\( \sigma \) "heavy" \( \rho \), the 50% atmosphere's \( (F_{10.7}, A_P) \) values are moderate and considered to produce "mean" or best-guess \( \rho \), and the 5% atmosphere's \( (F_{10.7}, A_P) \) values are relatively small and considered to produce 2\( \sigma \) "light" \( \rho \). Thus, as coasts for a given \( \bar{A} \) update are made with 95%, 50%, and 5% atmospheres,
Tiangong-1 Atmospheric Entry Predictions

t_{EI} estimates become progressively later to define an entry interface "window" having 2σ confidence.

The value for $A_i$ associated with a particular $t_0$ to $t_1$ arc reflects the mean of two effective drag area values obtained in the presence of a 50% atmosphere. The first component of this mean value achieves a near-null along-track position deviation $\Delta V$ from Tiangong-1’s TLE at $t_1$, while the mean value's second component achieves a near-null semi-major axis deviation $\Delta a$ from the $t_1$ TLE. Example iterations producing $A_i$ for a specific Tiangong-1 arc appear in Table 1.3

Table 1. Iterations in $\vec{r}_D$ reference area $A$ with a 50% atmosphere leading to near-null along-track position deviation $\Delta V$ (red) and near-null semi-major axis deviation $\Delta a$ (green) are reproduced for the coasting arc from $t_0 = 19$ February 2018 @ 10:39 UT to $t_f = 26$ February 2018 @ 09:45 UT. The final value for $A$ (blue) is the mean of those achieving the two near-null conditions and becomes $A_{24}$ in this analysis. The $\Delta V$ and $\Delta a$ associated with $A_{24}$ in this table are termed the iteration’s residuals.

<table>
<thead>
<tr>
<th>$A$ (m$^2$)</th>
<th>$\Delta V$ (km)</th>
<th>$\Delta a$ (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>28.138</td>
<td>+344.862</td>
<td>-0.947645</td>
</tr>
<tr>
<td>25.138</td>
<td>-6.236</td>
<td>-0.240152</td>
</tr>
<tr>
<td>25.192</td>
<td>+0.046</td>
<td>-0.252775</td>
</tr>
<tr>
<td>24.111</td>
<td>-125.471</td>
<td>-0.000690</td>
</tr>
<tr>
<td>24.108</td>
<td>-125.819</td>
<td>+0.000008</td>
</tr>
<tr>
<td>24.650</td>
<td>-62.958</td>
<td>-0.126195</td>
</tr>
</tbody>
</table>

The WeavEncke predictor [2] numerically integrates all simulated Tiangong-1 trajectory coasts. In addition to $\vec{r}_D$, WeavEncke simulates Earth gravity from the GEM10 model truncated to 7th degree and order. Also simulated in Tiangong-1 coasts is gravity from the Sun and Moon modeled as point sources.

Results

Figure 2 plots $A_i$ and $\bar{A}$ as functions of the associated $t_f$ UT. With little statistic weight early in this analysis, $\bar{A}$ tends to be relatively "noisy" and subject to change. As the number of $A_i$ values comprising $\bar{A}$'s running average increases, however, $\bar{A}$ statistic inertia grows. This imbedded history and insensitivity to short-term changes makes $\bar{A}$ particularly well-suited for simulated coasts to $t_{EI}$ over many weeks or months. Because $A_i$ values are localized in time with respect to $\bar{A}$, they must compensate for transient atmospheric heating effects from solar flares and geomagnetic storms affecting the real world $\rho$. Particularly at times late in this analysis, $A_i$ values would become influenced by changes in Tiangong-1's rotational state as it begins to tumble at higher rates in response to aerodynamic torques. Both $A_i$ and $m$ are subject to change if appendages are lost just before atmospheric entry.

3 As is evident from Table 1 values, $\Delta V$ is signed such that a positive value is down-track with respect to the TLE at $t_f$. To correct $\Delta V > 0$ toward a null deviation requires $A$ be reduced in the next iteration. Similarly, $\Delta a$ is signed such that a positive value has a larger semi-major axis (or, equivalently, mean geocentric orbit height) with respect to the TLE at $t_f$. To correct $\Delta a > 0$ toward a null deviation requires $A$ be increased in the next iteration.
Tiangong-1 Atmospheric Entry Predictions

Figure 2. Values for $A_i$ (green) and $\bar{A}$ (orange) are plotted as functions of anchor date $t_1$ as this analysis is conducted during the final half year of Tiangong-1's orbit lifetime. Although the two functions must have equal values initially by definition, there is no guarantee this condition will be approached to any great precision subsequently. But such appears to be the case for the final $A_{31}$ value with $t_1 = 1$ April 2018 @ 11:45 UT.

If Equation 1 were to perfectly model real world $\dot{r}_D$, each $A_i$ would be associated with $\Delta V = \Delta a = 0$ residuals. Figure 3's plot of these residuals as functions of $t_1$ helps quantify the degree to which Equation 1 idealizes reality when simulating Tiangong-1 orbit coasts. As intuition would suggest, residuals are greatest in magnitude as Tiangong-1 nears entry. The Figure 3 residuals spike in mid-March 2018 cannot be attributed to $\rho$ modeling errors alone. It is likely Tiangong-1 was in a chaotic rotational state induced by aerodynamic torques at this time. Another possible cause of this spike in residuals would be venting from pressurized onboard systems. A post-entry check of the Space-Track.org satellite catalog (SATCAT) indicates no unclassified debris associated with Tiangong-1 had been detected during the space station's orbit lifetime.
Tiangong-1 Atmospheric Entry Predictions

Figure 3. Residuals associated with $A_i$ iterations (reference Table 1's example) are plotted as functions of $t_l$. The along-track position residual $\Delta V$ function and scale are colored green, while the semi-major axis residual $\Delta a$ function and scale are colored orange. Note the null condition for $\Delta V$ is nearly 3 horizontal grid lines below the null condition for $\Delta a$.

Figures 4 and 5 are plots of $t_{EI}$ as a function of the associated anchor epoch $t_l$ for 95%, 50%, and 5% atmospheres. Entry predictions posted at Space-Track.org are included in these plots. In doing so, the associated message publication time is equated with $t_l$. In both figures, note how entry interface windows defined by the 95%, 50%, and 5% plots are enveloped within Space-Track.org markers with only one exception (namely the Figure 5 marker lying very close to the 50% plot). Once the 5% curve peaks with the latest $t_{EI}$ for $t_l = 19.4$ February 2018 in Figure 4, all subsequent entry interface windows converge in a consistent manner. That is, each window is contained within its predecessors.
Figure 4. For 95% heavy (red), 50% mean (green), and 5% light (blue) atmospheres, predicted $t_{EI}$ is plotted as a function of anchor epoch with $t_f$ extending from 18.6 September 2017 UT to 19.3 March 2018 UT. Contemporaneous predictions posted at Space-Track.org are plotted with black "X" markers.
Figure 5. For 95% heavy (red), 50% mean (green), and 5% light (blue) atmospheres, predicted \( t_{EI} \) is plotted as a function of anchor epoch with \( t_i \) extending from 19.3 March 2018 UT to 1.5 April 2018 UT. Contemporaneous predictions posted at Space-Track.org are plotted with black "X" markers.

The Figure 6 ground track plot reflects a 50% coast from the final \( t_i = 1 \) April 2018 @ 11:45 UT in Figure 5 to 22:00 UT. To inhibit premature termination of the ground track at the corresponding 50% \( t_{EI} = 1 \) April 2018 @ 22:28 UT, \( \ddot{r}_D \) is set to zero after 22:00 UT. This permits a reasonably accurate illustration of Tiangong-1 position at the time Space-Track.org declares actual atmospheric entry occurred: 2 April 2018 @ 00:00 UT.
Concluding Remarks

Analysis techniques documented in this paper have produced results satisfyingly consistent with Tiangong-1 atmospheric entry predictions appearing on Space-Track.org and in news media reports during the final months of this space station's orbit lifetime. The last entry prediction using these techniques, based on an anchor epoch of 1 April 2018 @ 11:45 UT, is about an orbit earlier than the 2.0 April UT entry time declared by Space-Track.org as actual. It should be noted the last TLE posted by Space-Track.org has an April 1 epoch of 16:07 UT, so there

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4 To reiterate remarks in the accompanying narrative, coasted motion after the start of Figure 6's ground track (off the coast of Yemen at 22:01 UT) is with zero drag acceleration because the associated $t_{EI}$ would otherwise be 1 April @ 22:28 UT, about an orbit earlier than the simulated current time at which Space-Track.org declares entry occurred.
Tiangong-1 Atmospheric Entry Predictions

appears to be no publicly available empirical data with which to infer a Tiangong-1 entry time to much better precision than about an orbit or 1.5 hours.

Given controlled satellite disposal techniques via destructive atmospheric entry routinely target the South Pacific Ocean (Mir and Progress being good examples), it would be hard to achieve a better outcome for Tiangong-1 than is indicated in Figure 6. This lends credence to speculation there may have been a non-propulsive means of controlling Tiangong-1’s entry trajectory to some limited extent. Speculation along these lines is further supported by a Reuters report published early in 2018.5 Do the Chinese have something to teach us about safe satellite disposal via destructive atmospheric entry?

References


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6 This document may be downloaded at https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19830012203.pdf (accessed 2 April 2018).