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Travel to Extraterrestrial Destinations Over Time: Some Exploratory Analyses of Mission Data

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Running title: Exploration of Extraterrestrial Mission Data

Abstract

This paper discusses data pertaining to space missions to astronomical bodies beyond earth. The analyses provide summarizing facts and graphs obtained by mining data about (1) missions launched by all countries that go to the moon and planets, and (2) Earth satellites obtained from a Union of Concerned Scientists (UCS) dataset and lists of publically available satellite data.

Introduction

The ultimate goal of this research project is to search for quantitative trends that describe humankind's advancement in the physical exploration of extraterrestrial bodies. The objective of the research described here is to perform preliminary, yet critical, steps toward that ultimate goal. Specifically, we seek to identify sources of data about space exploration missions, extract pertinent facts about the great majority of missions rather than a sampling of missions, and perform exploratory analyses on the extracted facts to better understand the data and domain. We seek data on all missions rather than just a representative subset because the total number of missions is manageable – in the hundreds for missions to extraterrestrial bodies and in the thousands for missions into orbit around Earth.

There are a number of aspects to space exploration. One is the science – how the universe works and what is happening in distant stars and galaxies, and even the far reaches of the observable universe. One traditional approach to measuring scientific progress is paper and citation counts. While such counts clearly measure activity, they don't necessarily accurately reflect the amount of advancement in human knowledge, and indeed, it is not clear how to accurately do this in a quantitative way. Advances in knowledge are often unique and differ in important ways, and thus are hard to compare in terms of quantitative amount of progress. Which is a bigger advance, for example, special relativity or Newtonian mechanics, and by how great a percentage? From the standpoint of actual travel to extraterrestrial bodies, the science – perhaps in some ways unfortunately – becomes secondary to the fact of getting there. A mission that lands on the moon for the primary purpose of competition with other countries (as was the case between the US and the Soviet Union during the "space race" period) lands on the moon as much as one that successfully executes a mission intended to squeeze every ounce of science possible out of a moon landing.

To summarize, the four main objectives of this research, including both overarching and specific to this paper, are as follows:

1. identify quantitative trend lines that permit extrapolations predictive of future human space exploration activity;
2. identify sources of data to support item 1 above;
3. develop a data set that covers much of or most relevant activities rather than relying on a sampling strategy; and
4. do exploratory mining of the dataset.

Background

The performance of space exploration technology must be understood, first, by collecting data from which the performance can be extracted. Data collection and analysis is an intrinsic part of the space exploration endeavor in multiple ways. Big data has become a high profile term as well as field of both research and practice in recent years. Space science and technology is no exception. NASA, for example, has numerous projects that relate to handling and analyzing big data (Savaram 2017). One of the high profile missions, the Pluto contact of 2016, provided a special challenge in getting all the data that was acquired downloaded to Earth over the several light hours of distance required (Stockton

2016). Space, after all, does not support high bandwidth commercial data trunks. Stefano *et al.* (2017) address the data storage and management part of the problem with an IT platform, Eodataservice.org, designed for space mission data needs.

Focusing on technical performance over time, one approach is to focus on "bang for the buck," that is, amount of the technology per dollar. This is the "Carlson curve" approach commonly used in measuring technical performance over time of biotechnology (NHGRI 2017). Wright's (1936) law used this approach. For space exploration, costs tend to be high and cost-per-performance is generally an important engineering issue. For example Cordova and Gonzalez (2017) analyze NASA's "Faster, Better, Cheaper" program, which focused on this aspect but was deemed not successful. Thus, for a country to have a space program, it must be willing to spend the necessary funds. Luxton (2016) presents lists of countries that spend significant money on space exploration. Unfortunately the figures are just for one year. Expenditures are not necessarily easily available for all years, thus enhancing the interest of non-monetary measures for which the data might be easier to obtain. Multi-year data on space related financials is provided by Bryce (2017). However the data is limited to startup investment, which while it captures an important part of the space funding picture that is often proposed as auguring a transition to commercial development of space related industry, does not capture the overall picture of space funding in general or, more specifically, space exploration per dollar.

Due in part to the difficulties associated with obtaining the data to measure technical performance per dollar for space exploration, pursuing measures that rely on performance without reference to costs is a natural strategy. With respect to space exploration data, Eshbach and Hathaway (2014) provide an online service showing how many people are in space at the current time. As of the moment of this writing, the web page lists six names, their mission roles, and how many days each has been in space. Duffy (2015) assesses 2015 as a banner year for space exploration.

To get at trends over time it is necessary to obtain data and provide assessments spanning time. Hicks (2015), focusing on crewed missions, concludes that "It's sad that human space exploration has stalled." Oukaci (2017) argues that space exploration is slowing. Bardi (2015) is even more pessimistic, suggesting that "… human spaceflight is coming to an end" and providing a graph of human space flights 1960–2014 to illustrate his fears. Technologies often develop in an exponential fashion. Although it is early enough that the data regarding space exploration does not yet lead to definitive conclusions, Adams (2015) provides a graph and blames the lack of commercial use of space as a specific reason for why space exploration has not yet demonstrated a clear case of exponential development.

Arguing that a pessimistic assessment of advancement in space exploration is not warranted, Roberts (2011) describes how progress is proceeding in multiple ways that, while genuine, do not jump out from much commonly tabulated data. Flo422 [sic] (2017) charts the number of people launched into space per year, 1961–2016. Elliott (2014) plots the population of space over time; the "collapsed view" mode clearly suggests a trend of increasing human population of space over time. In previous work in our lab we identified a model for measuring space exploration activity. This model was tested only on NASA data, and with that limitation in mind the model nevertheless suggests generally increasing technical performance (Hall *et al*. 2017).

To understand human space exploration, it is necessary to analyze the data available on space missions. Data from NASA (2018) is an integral part of a larger whole that incorporates data about the space missions of all countries. McDowell (2017) accounts for satellite launches worldwide. The Union of Concerned Scientists (UCS 2017) maintains a catalog of currently active satellites. Space exploration seems to appeal to enough Wikipedians (mostly volunteer editors) that Wikipedia's information is kept up to date and has reasonable coverage of satellite activity (Category 2018), general space mission lists broken out by year (Timeline 2018), and many related listings. The dream of human exploration of extraterrestrial bodies remains before our eyes, tantalizing the imagination with its potential (Berleant 2017).

Results

Missions to extraterrestrial bodies

For the next several figures, missions in which spacecraft were sent to extraterrestrial bodies were recorded. Missions were scored according to the type of contact made with the destination body. The scoring assigned 2 points to a launch failure, 3 to a distant flyby, 6 to a close flyby, 9 to orbiting the destination, 12 to a hard (destructive) landing, 12 to a return to Earth, 15 to a soft landing, 17 to a crewed mission, and 18 to a mission with a robotic rover. This represents an adjustment to the values used in Hall *et al.* (2017). Many missions qualified for multiple categories, and were

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assigned to the score of the highest-scoring category for which it qualified. The scores of the missions launched in a particular year were summed, and the % of the sum that was attributable to various countries was calculated and graphed from year to year.

Figure 1 shows the % of the summed scores of missions for each year attributable to US launched missions.

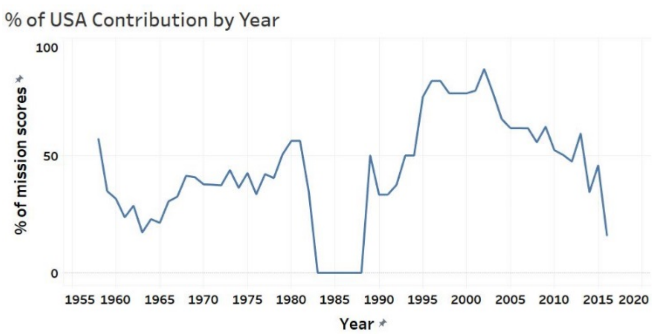

Figure 1. Percentage of missions launched by USA.

Figure 1 was plotted by using moving averages to smooth out yearly fluctuations in the data. The value for a given year was calculated by averaging the raw values of that year and the four previous years. The graph reached its maximum in the year 2003.

Figure 2 shows the data for the Soviet Union and its successor state Russia. From the graph we can observe that there is a major contribution from the USSR/Russia in the initial years. Later the contribution falls rapidly and remains low thereafter.

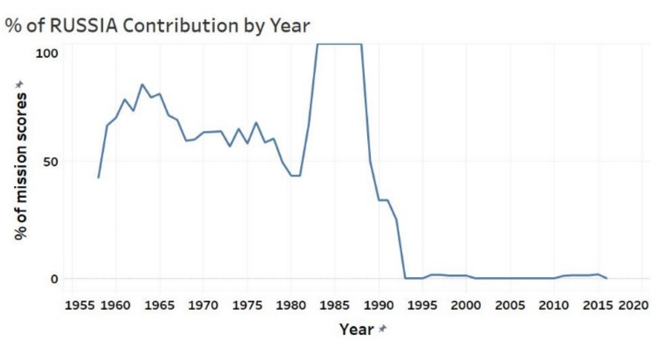

Figure 2. Percentage of missions launched by USSR/Russia.

Figure 3 shows the situation for Japan. Compared to the US and the USSR/Russia, Japan has zero contribution initially, then ramps up a space program that makes significant contributions to the world's exploration of extraterrestrial bodies.

Figure 4 shows the relative activity of China. We can observe that China started exploring astronomical bodies relatively late but has been increasing its share of missions on a generally increasing trajectory.

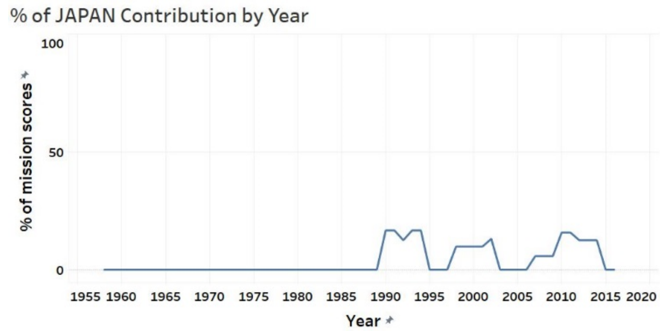

Figure 3. Percentage of missions launched by Japan.

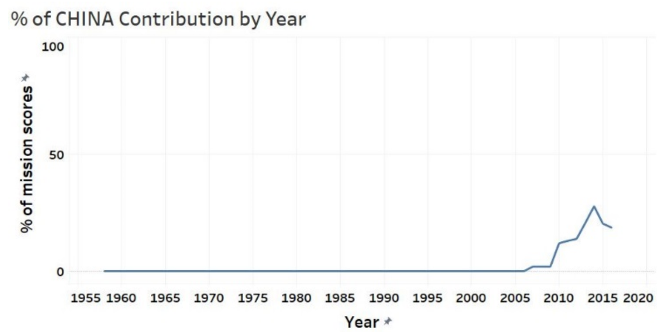

Figure 4. Percentage of missions launched by China.

Figure 5 shows the situation for European-launched missions. Europe did not contribute to launching missions to astronomical bodies at first. More recently Europe has been a significant contributor to such missions.

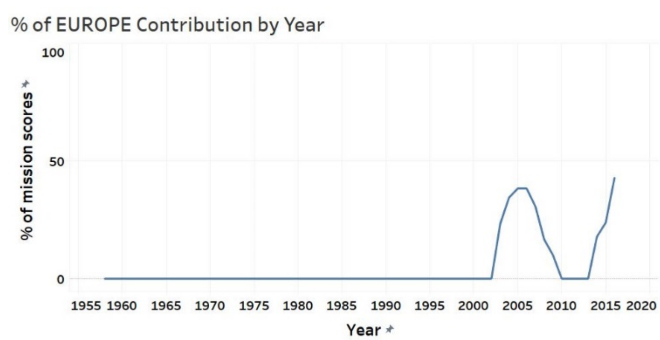

Figure 5. Percentage of missions launched by Europe.

The next graph, Figure 6, shows the smoothed percentages for India.

It is possible that with efforts such as SpaceX, the costs of lifting mass into space will be reduced and this might lead to more launches in the coming years.

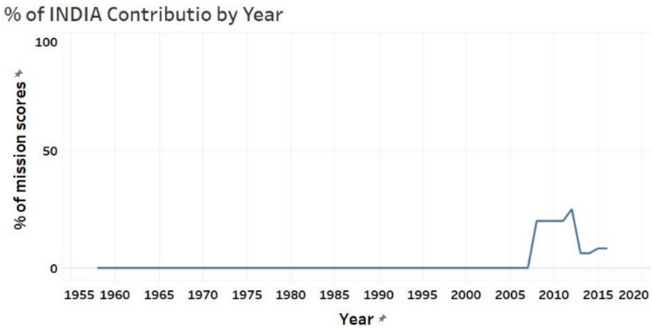

Figure 6. Percentage of missions launched by India.

Satellites

Extraterrestrial bodies are only one category of space mission. Another category is satellites, of which the vast majority are around the Earth. These satellites are one variety of humankind's expansion into outer space. Satellites gather data that is otherwise unobtainable, provide services such as GPS and radio transmission that are not otherwise possible or economic, and form an important portion of our space exploration activity. This subsection provides some analyses of satellite data.

Purpose is a key column in the Earth satellite dataset used by the Union of Concerned Scientists (UCS 2017) that we downloaded for analysis. Figure 7 shows a facet chart that we developed to show the satellite launches by year, differentiated by the purpose of the satellite, for satellites that were operational as of 9/1/2017. The chart shows growth in communication satellites over time, and growth in Earth observation satellites starting a bit later. Following that, there was a gradual increase in technology development satellites. Space science shows steady growth in recent years. Technology development satellites launches very late in the timeline compared to Communication satellites or Earth observation satellites. The differences in the timing of the increases in these categories is of interest as it permits comparing the categories over time. Overall, communication satellites have constituted the largest category of Earth satellite launches. What are the implications of these observations? One may hypothesize that these trends reflect trends in underlying need by society for satellites with those purposes.

Another data element in Earth satellite dataset we analyzed (UCS 2017) is the launch site. A histogram chart was developed for active Earth satellite counts by launch site. Figure 8 shows that the highest number of currently active Earth satellites were launched from the Baikonur Cosmodrome.

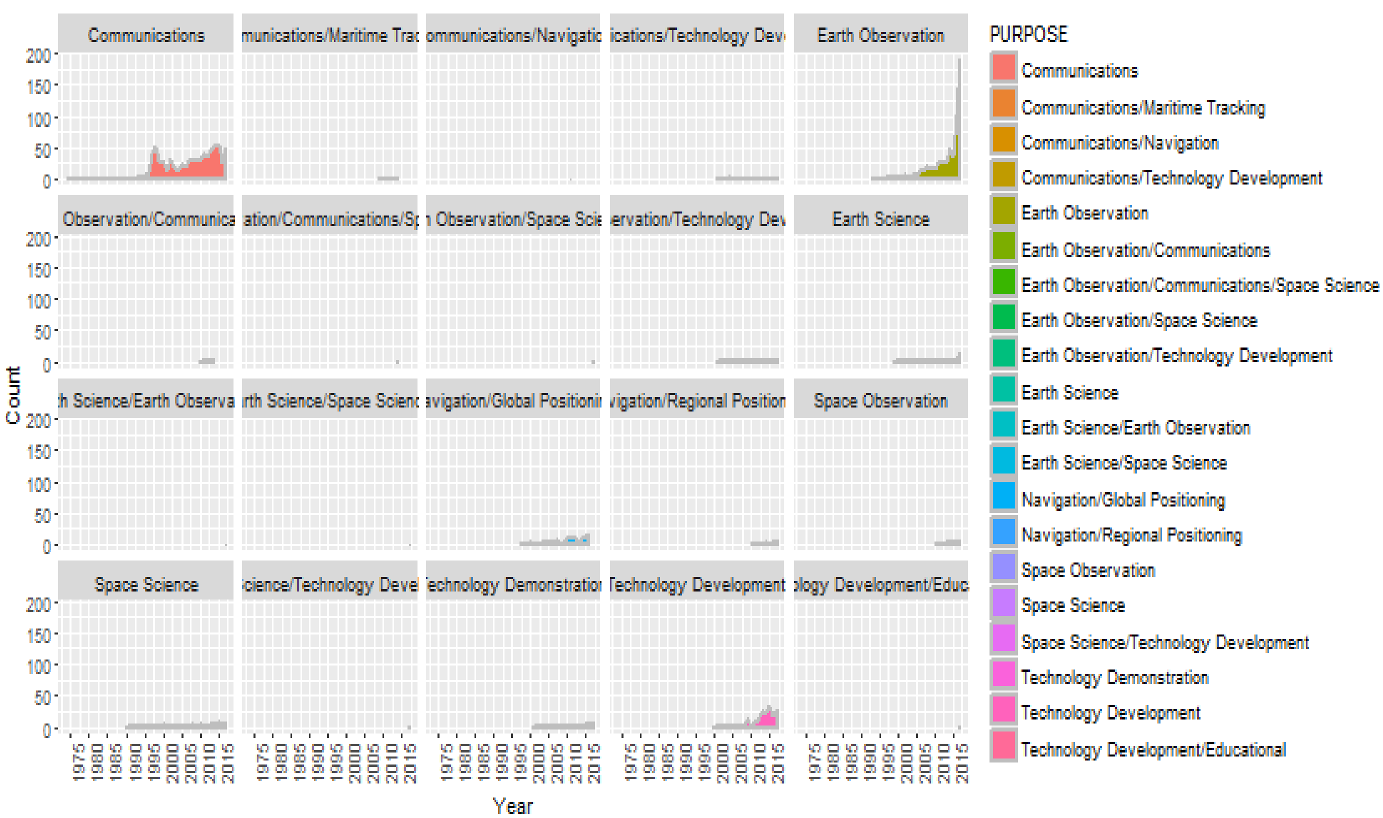

Figure 7. Purpose categories of artificial satellites.

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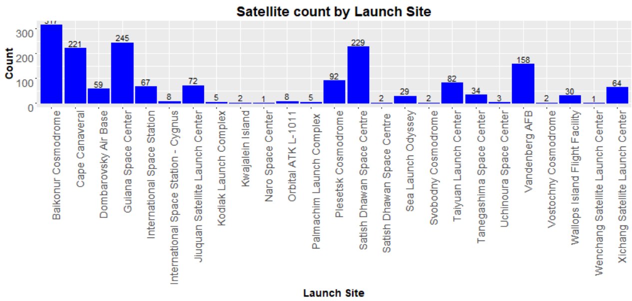


Figure 8. Active satellites by launch site.

Obviously, the Baikonur Cosmodrome is one of the world's largest and most active space facilities. The chart shows that Baikonur Cosmodrome leads with 254 launches of active (as of 9/1/2017) satellites, followed by other launch sites, notably Guiana Space Center, Cape Canaveral, and Vandenberg Air Force Base. The Guiana Space Center is in French Guiana and began operating in 1968. Reasons for the location include being near the equator, so that the spinning Earth gives launches a faster boost thus minimizing the energy needed to launch into space. Also, sea east of the spaceport provides a measure of safety in that launch debris has a place to fall without endangering people on land. French Guiana is in South America and is a part of France.

Apogee and perigee distances are two of the data elements regarding satellites in the McDowell (2018) dataset. A scatter plot of average apogee vs. average perigee for Earth satellites was developed using that data. Note that apogee and perigee (peri- is from Greek and means near) may be defined as follows.

- **Apogee**: that point in an orbit at which the orbiting body is furthest from the center of the orbit.
- **Perigee**: that point in an orbit at which the orbiting body is closest to the center of the orbit.

Figure 9 shows that the average apogee and perigee of satellites in orbit has increased over time. Most of the satellites have an apogee significantly greater than the perigee. Furthermore, the larger apogees and perigees tend to be associated with newer satellites.

Patterns in data on perigee and apogee were further studied using the k-means clustering algorithm on the UCS (2017) dataset. Figure 10 uses 2 clusters to identify similarities in the data. Color depicts the purpose of the satellite. The graph shows that all the earth observation satellites are grouped at a relatively close distance and communication satellites are grouped at further distances. The graph shows a pattern of most of the Earth/Space Science, Navigation/Global Position and Earth science satellites located centrally on the chart. Cluster 2 does not contain any the Earth/Space Science, Navigation/Global Position or Earth science satellites.

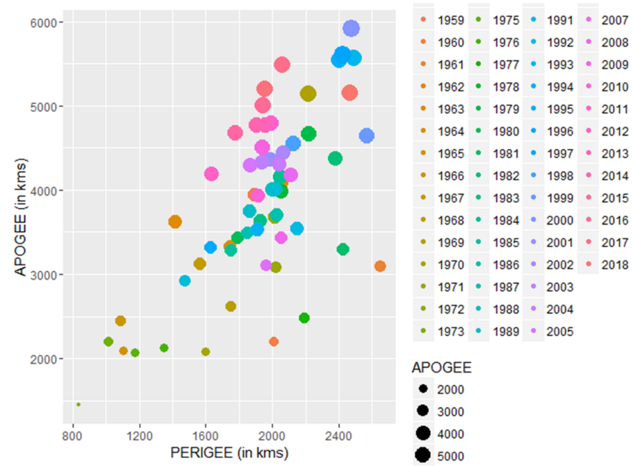


Figure 9. Apogee vs. perigee for Earth satellites. (Color coding is viewable on a computer display.)

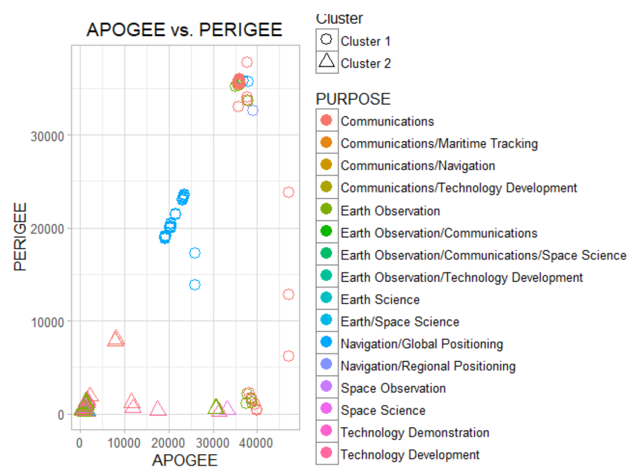


Figure 10. Clustering of satellites on the basis of their orbital distances.

McDowell (2018) provides a lengthy compendium of basic data on satellite launches worldwide. Satellite launch data were extracted from the web site, cleaned, and analyzed. Figure 11 shows some of these results. These data indicate that the fraction of satellites that are successfully launched into orbit, out of all satellite launches, has tended to improve over time. This is a positive trend.

Figure 11 shows a spike around 1998. The Union of Concerned Scientists (UCS 2017) dataset was analyzed to better understand it. Figure 12 resulted, showing a corresponding spike. A closer investigation of the data revealed that the spike was due to communication satellites launched between 1997 and 1999. While the data do not explain why, these visualizations do highlight the fact that it occurred, thus suggesting an exploration of the "why?" question.

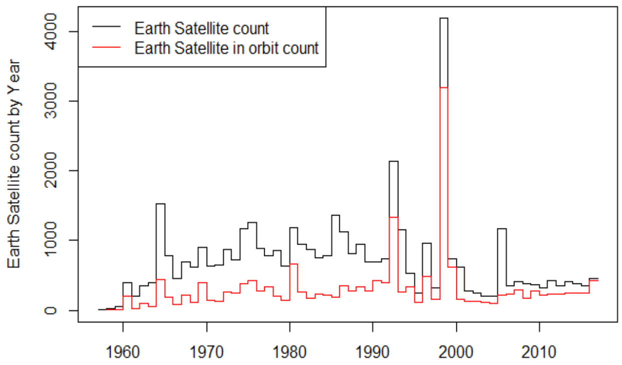


Figure 11. Total satellite launches and successful satellite launches.

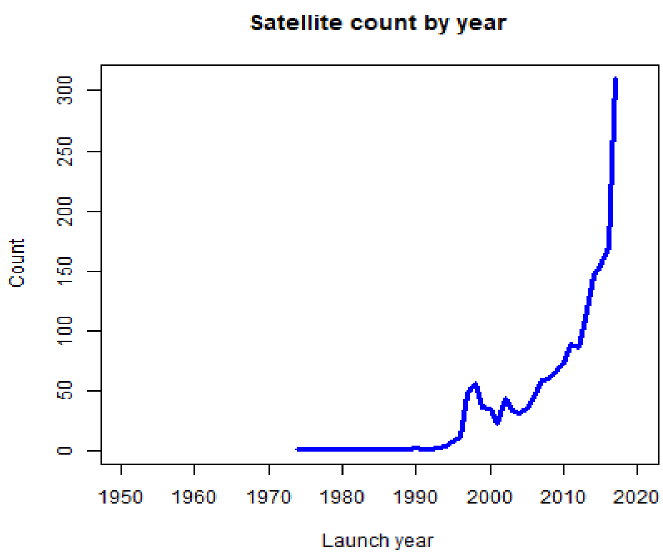
Another analysis is shown in Figure 13. Different countries have different numbers of satellites in orbit. A comparison of operating (as of 9/1/2017) Earth satellites owned by different countries was done using the Union of Concerned Scientists (UCS 2017) dataset. A histogram chart was developed showing country vs. number of operating satellites. Figure 13 shows that the highest number of Earth satellites in orbit are owned by the US with a count of 786, followed by China at 203. Russia has a count of 138. The chart shows total 81 countries involved in the satellite launches. Overall, it seems like many countries have satellites but still have a long way to go to catch up with the US.

Discussion

There are several possible goals for mining space mission data. These fit into two broad categories: understanding what has been accomplished (the past), and understanding what is possible (the future).

Goals related to the past focus on historical understanding. These include the following.

- *The reasons, results, and social effects of the space race between the US and USSR decades ago*. For example, there was a burst of early space exploration activity early on known as the "Space Race." The degree of activity was higher than expected given the longer term trajectory of more gradual progress in space exploration. That level of activity was not sustained, because once people landed on the Moon the race seemed to have been "won," as though space exploration was akin to a sports contest, and having been "won" it lost some of its attraction and thus US government funding decreased.
- *The satellite infrastructure, its effects on communication, and the effects of the communication thus enabled on the evolution of the current world order*. Unlike most space related activities, satellites have a lot of commercial and other practical applications. This has driven much of the satellite construction and launching activity, a force that does not apply to other space exploration mission types such as those to distant planets.



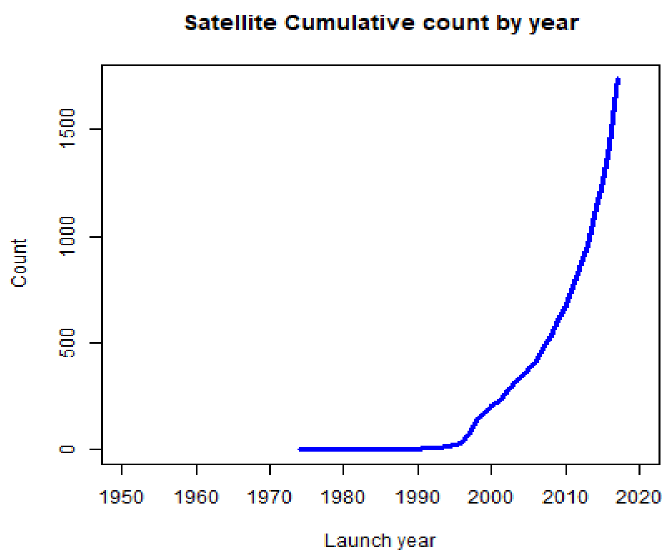


Figure 12. Satellites that were operational on 9/1/2017. (Left) Number launched in a given year. (Right) Number launched in or before a given year.

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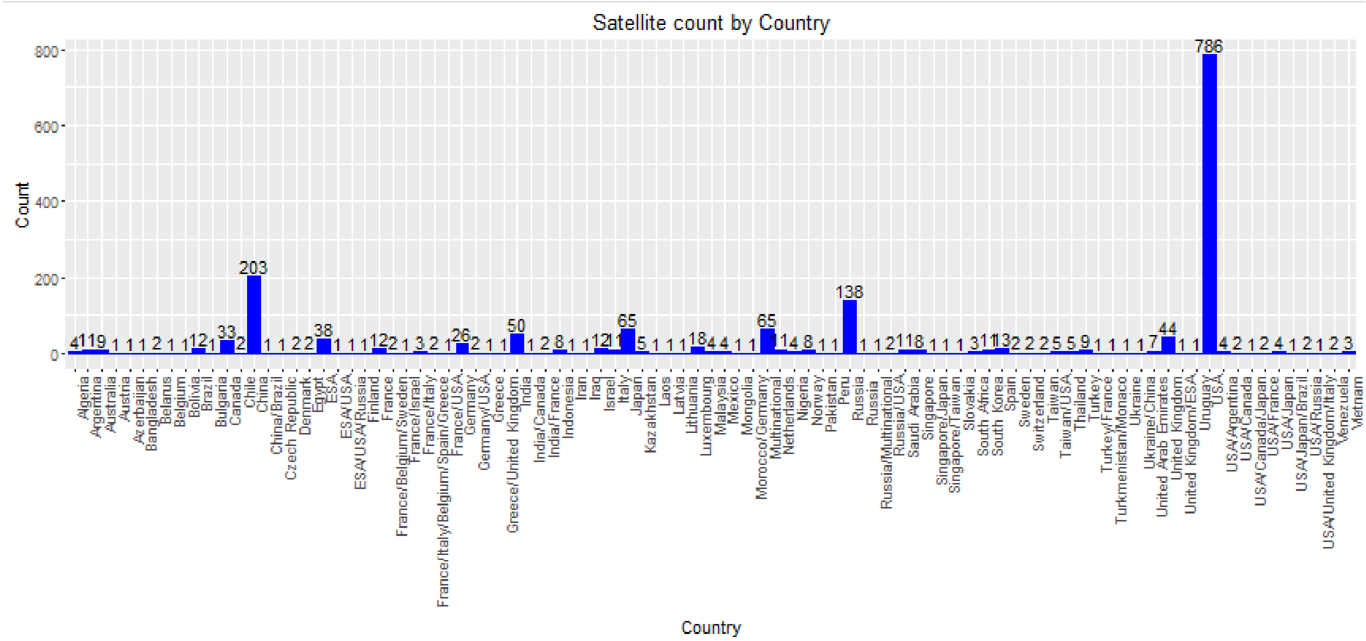

Figure 13. Number of satellites in operation by country

- *The effects of long-standing popular cultural interests on large national science and engineering efforts*. This is evidenced by the differences in efforts made to travel to extraterrestrial bodies with historically strong ties to popular consciousness and imagination like Mars (Crossley 2011), compared with efforts to travel to bodies with weaker such ties.
- *The experimental testing of laws that govern and describe trends in technological performance*. Exponential and similar trends are examples. Less quantitative examples include effects of population, societal wealth, and previous technologies on technological advancement. Historical data can be used to test if such a proposed law has held in the past.

In contrast to understanding the past, goals related to understanding the future use data about the past for predictive purposes. These purposes include the following.

- *Technology forecasting of future space exploration.* If a trend can be quantified based on historical data, it could be extrapolated to make predictions about future levels of space exploration activity.
- *Technology foresight of likely scenarios of future space exploration.* The future will always be fraught with uncertainty. The concept of foresight is distinguished from forecasting in that it is about determining future possibilities rather than predicting which one will occur. Because of the inherent uncertainty about the future, foresight is a reasonable approach to understanding the future of space exploration.
- *Insight into effective national or corporate policy options for future space exploration efforts.* Interest in the future of space exploration (or other technologies) is not just about what will eventually happen. There is instead the possibility of affecting that future. There are always reasons to pursue certain futures over others. Understanding and evaluating different scenarios leads naturally to efforts to make the most desirable ones happen.

Conclusions and Future Work

We have collected data and performed exploratory analyses. The ultimate goal, however, is to see if we can extract an overarching trend that will permit understanding of likely future levels of space exploration. Such a trend would be analogous to Moore's law for computer chips and other exponential curves describing technical performance over time for various technologies.

A trend curve, by definition, can be extrapolated to make predictions about the future because it shows a trend. Such predictions are testable by checking if the predictions hold when the data finally becomes available. On the other hand, a curve from which no extrapolatable trend can be determined provides little basis for projection and thus does not support technology forecasting. Thus for forecasting purposes a curve that shows a trend is better.

How can a trend curve be found? First, there must be an underlying trend in order for a valid trend curve to exist and be found. This is a modeling problem. Satellite launches and visits to extraterrestrial bodies, which we analyzed herein, are obvious candidates for model components. It is not clear however if those components are sufficient. Other components that might need to be accounted for are the following.

- *The International Space Station*. The space station is not an astronautical body and, while a satellite, is a much bigger part of the whole space exploration picture than an ordinary satellite. Most astronauts currently go there, for example. If it were not for the existence of the International Space Station (ISS), perhaps other exploration activity would be done instead. Activities related to the ISS have constituted a significant portion of space exploration during the period of existence of the ISS.
- *The US Space Shuttle program*. Like the ISS, the US Space Shuttle program made up a significant fraction of the overall space exploration effort, but is not represented adequately when focusing on satellites or interplanetary missions. Data (e.g. Catlett 2004) exists that may support including the Space Shuttle program in a model of space exploration.

To properly model space exploration activity, various parameters must be defined. For example, does a trip to the moon count less than a trip to Mars? By how much? Also different types of contact with the destination need to be distinguished. For example, a soft landing with a rover and a return trip should presumably count more than a flyby. We have done this in an ad hoc manner as described earlier. A principled approach to inferring these numbers would be better, but it is not clear what is the best way to do it.

One approach to the parameter tuning problem posed by the foregoing paragraph is to seek parameter values that result in a space exploration trend curve that is relatively smooth and extrapolatable. But is determining parameter values that way fair? Here, in a nutshell, are the “no” and “yes” arguments.

- *No, it is not fair*. The counterargument to choosing parameters that result in an extrapolatable curve is simply that it looks too much like an attempt to force fit the data to a curve. It appears to be the dual of the overfitting problem in machine learning: instead of finding an overly complicated curve that fits data that might in fact be more noise than signal, this approach involves finding a complicated transformation of the data values to fit a simple curve.
- *Yes, it is fair*. A set of parameter values that results in an extrapolatable curve is not, in itself, a claim that the curve is a valid model for space exploration activity over time. As just discussed it might be no more than a force fit of the data with no predictive value for future years. On the other hand, it might turn out to have the desired predictive ability, and thus be part of a useful model. Only time can tell which possibility applies, but one thing that can be known immediately is that the parameter values form a hypothesis. This hypothesis will be tested by future events. If future events follow the resulting curve’s extrapolation, that is corroborating evidence for the hypothesis (i.e., the model and its parameter values). If future events do not comply with the extrapolation, that is evidence against the hypothesis.

Different sets of parameter weights would provide different hypotheses, and these each can be tested against future events. If a set of parameter weights can be justified by domain facts and historical context, the hypothesis embodied by that set of weights gains explanatory heft as well. Ultimately a model of advancement in space exploration over time may be derived that, like the exponential and other laws shown to be useful with various other technologies, will be shown to predict future levels of space exploration activity.

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