NASA Space Flight Instruments: Cost Time Trends

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Are NASA's space flight instruments becoming cheaper or more expensive as time marches forward? After analyzing the costs of hundreds of instruments launched over the last 30 years, the short answer to this question is no… and yes.

Nomenclature

CER	=	Cost Estimating Relationship
Cost	=	All costs are Fiscal Year 2004 Dollars
NICM	=	NASA Instrument Cost Model
PCA	=	Principle Component Analysis
SNR	=	Signal-to-Noise Ratio

I. Introduction

THIS paper gives a visual analysis of the cost time trends for various NASA space flight instrument types, such as optical, particles detectors, fields detectors and microwave instruments. In addition to the statistical approaches utilized, such as significance tests, cluster analysis and principle components analysis (PCA), we will also discuss the intangibles which are likely at play, including technological progress, NASA policy and the luck of the draw associated with mission manifests.

This analysis was performed as the main driver for the NASA Instrument Cost Model (NICM) recent cost estimating model redesign. Started in 2004, the first version of NICM was based off of instruments launched from 1985-2005, or 20 years' worth of data. As NICM hit its 10-year anniversary, we wanted to know: should NICM continue to only use the most recent 20 years' worth of data (1995-2015)? Are instruments becoming cheaper or more expensive as time marches forward?

II. Executives Summary

There is evidence in favor of a drop in the median dollar-per-kg value across some instrument types, but little in others. Whereas further research is needed to substantiate, Particles and Optical-Planetary instrument types show moderate to strong evidence of a downward trend in dollar-per-kg. Further research is required to study the nature of this trend (shift, taper, cyclic, etc.). Little evidence for a similar downward trend was detected for Fields or Microwave instruments, or Optical instruments on Earth Orbiting spacecraft.

III. Evaluation Process

Figure 1 shows the process our team used to evaluate the impact of time on historical NASA science instrument cost. This process took a three-tiered approach to analyzing the data, each tier providing guidance to the next tier's more detailed assessment. Data exploration, using visualizations such as cluster trees and box-whisker plots of the data binned according to intervals of time, initiated the first tier of this analysis. This enabled observation and visual inspection of top-level relationships in the data, and identified slices of the dataset on which to pursue further analysis.

The next tier of this process took a first step in the direction of a statistical analysis of the data, looking for significance of potential time trends observed in the data exploration phase of the process. Sensitivity of significance results to assumptions of normality and independence was also addressed.

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The final tier of this process, a rigorous time series assessment of instrument costs where moderate to strong evidence exists for a time trend, remains future work. This more sophisticated analysis, utilizing various forms of auto-regressive models, could further elucidate the nature of the trend, its statistical significance and aid forecasting of instrument costs for future developments.

The remainder of this discussion focuses on the methods and results used in the first two tiers of this analysis.

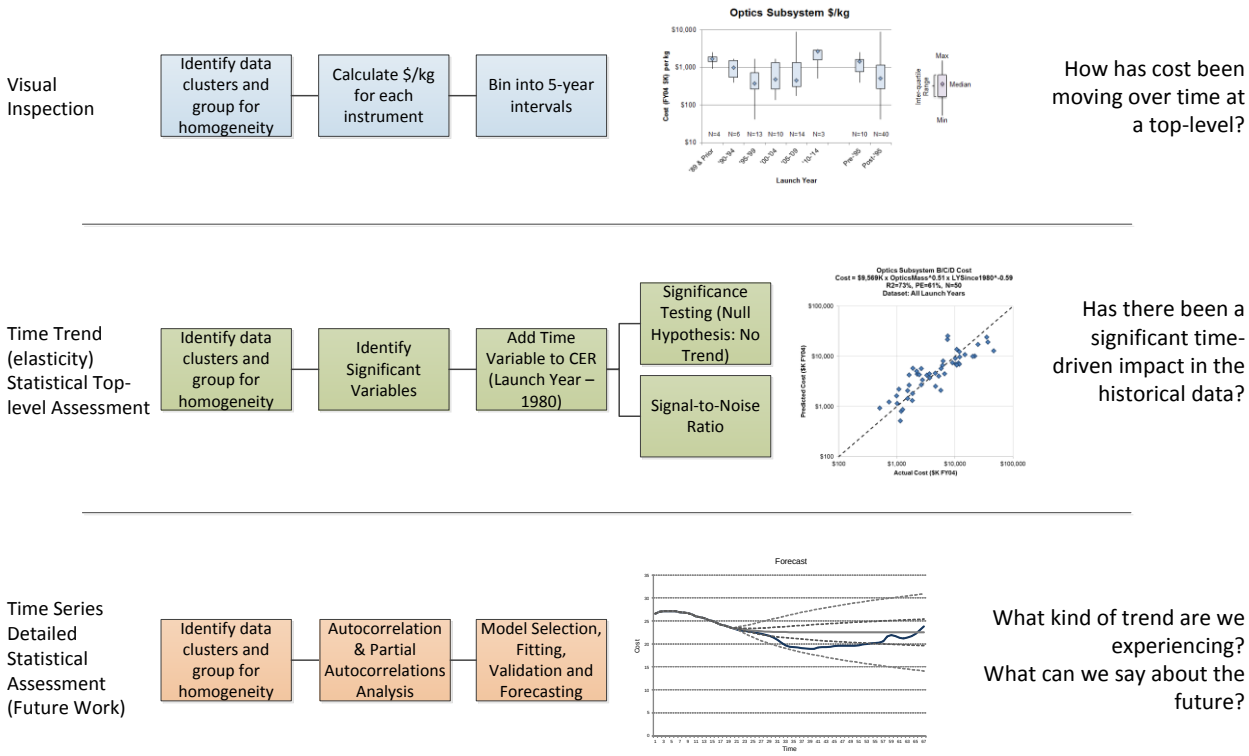

Figure 1. Time Trend Evaluation Process of NASA Science Instruments. *This analysis takes a three-tiered approach: (1) Visual Inspection to explore and understand the data, make initial observations and direct the path forward to a more detailed statistical assessment and time series analysis. (2) Top-Level Statistical Assessment of Time Trends initiates this more detailed assessment by looking at preliminary significance results of candidate time trends identified in (1). Ultimately, a rigorous time series assessment (3) would be done to assess the nature of observed time trends, their significance and address how we may be able to forecast instrument costs for future developments.*

A. Data Exploration and Visual Inspection

Cluster analysis and box-whisker plots were used to explore and visualize relationships in the data in order to guide further analysis. Agglomerative complete clustering was used to aid identification of homogenous groups within the data when estimating statistics and pursuing further regression analysis. While the choice of this specific mode of clustering does not preclude use of other clustering methods (and insights gleaned from them), this method was chosen since it allows the data "speak for itself" in terms of separation into groups (number of groups is not provided as input to the model, as in, for example, k-means clustering) and makes no distributional assumptions (as in, for example, the EM algorithm).

For this application to NASA science instrument cost trends, inputs to the cluster analysis were total instrument cost, as well as cost drivers, including total instrument mass, maximum power, design life, peak data rate, development schedule duration (NASA phases B/C/D), launch date and other quantifiable subsystem level characteristics. After normalizing data and considering potential outliers, the data was transformed into log-space since the relative percentage difference between individual instrument observations is more meaningful when assessing cost and cost

drivers. After applying this transformation, a standard Euclidean metric was selected to quantify separation between individual data points. Hence, the distance *d* between two instrument observations is defined as:

$$d(x,y) = \sqrt{\sum_{i=1}^{n} \left[\ln\left(\frac{x_i}{y_i}\right)\right]^2} \tag{1}$$

where $x, y \in R^n$ are two instrument observations in the data set, each composed of *n* technical and programmatic attributes (mass, power, cost, etc.).

The supremum norm was used to gauge the distance *D* between clusters, utilizing the maximum distance between data points in one cluster versus the other:

$$D(S,T) \max_{x \in S, y \in T} d(x,y) \tag{2}$$

where *S* and *T* are disjoint subsets of instrument observations.

Employing this norm aides visual inspection of the resulting cluster tree, making the separation between clusters more evident (avoids "chaining") and increasing dissimilarity from sub-cluster to cluster (avoids "inversion"), easing interpretation.

Analysis of the composition of clusters and review of these results with instrument developers determined primary groups in the data to be driven by instrument type: Optical, Microwave, Particles and Fields instruments. Destination (Earth orbiting, Planetary) also showed evident separation in the data, particularly within the subset of optical instruments. For further discussion of this clustering technique, please see Ref. 1.

For each of these instrument types, standard box-whisker plots were employed as a tool to visually inspect how, at a top-level, the empirical distribution of dollar-per-kg has changed over time. Figure 2 shows an example of the box-whisker plot format used in this analysis. Each plot bins the data in two contiguous time-dependent ways based on launch year: by 5-year bins (on the left) and by pre-1995 / post-1995 bins (on the right). A "pre-1990" bin is used for all observations in the dataset launched prior to 1990; however, the earliest launch date in the dataset used for this analysis was 1988, so the reader should be aware that the sample in this bin may not be representative of a full 5-year interval of time. Other 5-year bins are considered representative of the time period for the type of instruments studied in this analysis of the data population and data collection effort.

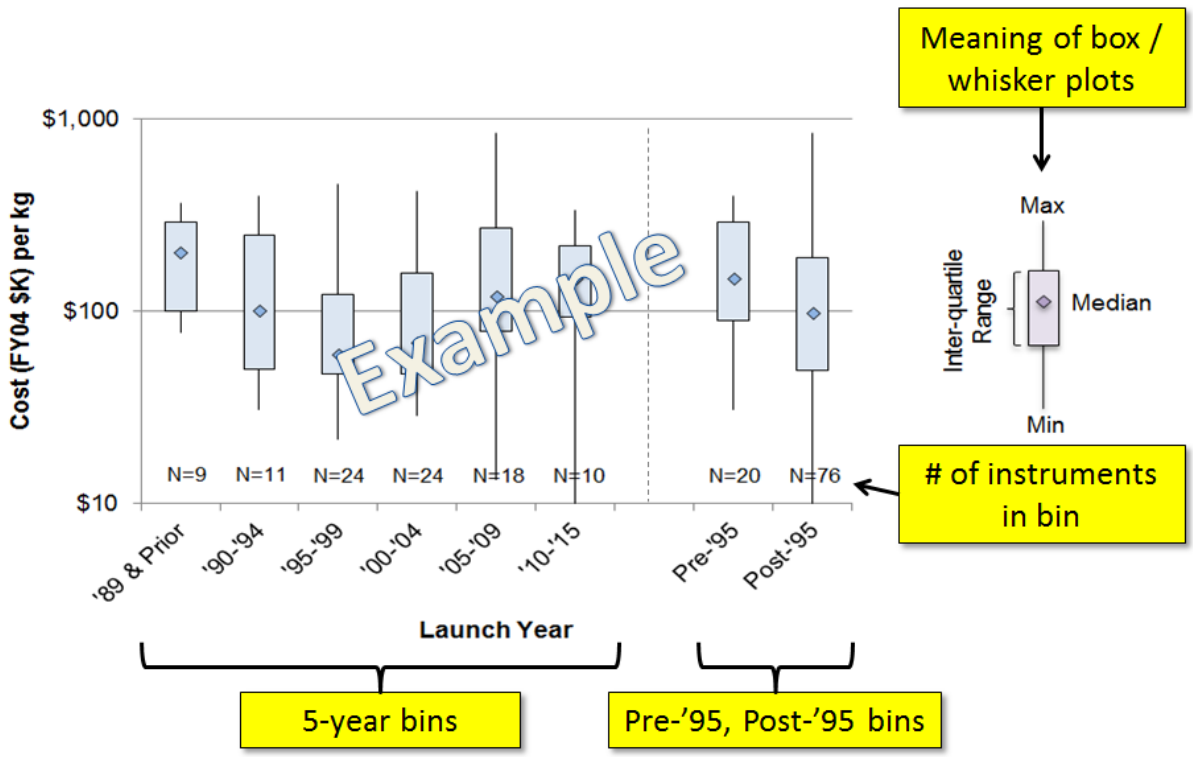

Figure 2. Example Box-Whisker Plot: *The box-whisker plots used in this analysis, depicting the dollar-per-kg distribution for NASA science instruments (vertical axis; note the log-scale), grouped into for 5-year bins (left-horizontal axis) and pre-'95 / post-'95 bins (right-horizontal axis) according to year of launch. Above each bin is a diamond: denoting the median dollar-per-kg for that bin; a box: denoting first and third quartiles of the dollar-per-kg data; and "whiskers" (vertical lines coming out of the boxes): denoting minimum and maximum dollar-per-kg for instrument data in that bin. Also shown on the chart is the number of observations in each bin, N.*

Above each bin is a diamond denoting the median dollar-per-kg for that bin; a box denoting first and third quartiles of the dollar-per-kg data; and vertical lines coming out of the boxes, the "whiskers," denoting minimum and maximum dollar-per-kg for instrument data in that bin. These two bin sizes were selected for this analysis based on available sample size, the requirement (for statistical reasons) that they partition the time interval into disjoint, contiguous, equal length intervals, and that they make intuitive sense readily comprehensible for this exploratory phase of the data analysis. Bin sizes across other time intervals was explored, but either did not have enough data, did not make a significant difference in observation, or did not have the intuitive appeal for ease of data inspection. Note that the number of observations in each bin, N, is also shown above the horizontal axis of the plot.

B. Time Trend as an Elasticity: A Preliminary Statistical Assessment

After getting a sense for where instrument costs have changed over time, regression analysis was performed as a first step to explore the statistically significance of these changes. This was done by applying a simple power model (i.e. linear model fit in log-log space) to the data:

$$Y = \beta_0 \left[\prod_{i=1}^{n} X_i^{\beta_i} \right] \epsilon \tag{3}$$

Where Y is the cost of the instrument, dependent on variables X_i (for example, total mass or maximum power of the instrument); β_i are parameters derived from a fitting process to the data (β_0 is sometimes referred to as the *scaler* term of the model; β_i, $i > 0$, the *elasticity* of Y associated with the variable X_i); and ϵ is an error term such that $\ln(\epsilon)$ has mean 0 and common variance σ^2. Note that no distribution is placed on ϵ (or $\ln(\epsilon)$) at this point; only a zero mean and constant variance (in log-space).

More complex models can be entertained, but this simpler model form captures the typical elastic nature of cost with cost drivers (e.g. mass), and is adequate as an initial step to a more sophisticated trend analysis (e.g. time series analysis making use of various autoregressive models). This model also allows us to clearly identify the impact of each variable on instrument cost in the presence of other variables, and assess statistical significance. To apply and specify this model to the data, variables impacting instrument cost were identified and assessed for multicollinearity (e.g. total mass and maximum power tend to be collinear). In a step-wise manner, candidate variables were included or excluded from the model based on significance testing, maximizing fit to the data (R^2) and minimizing prediction error (utilizing bootstrap cross validation). The regression technique employed principal components analysis when multi-collinearity was deemed significant; otherwise, ordinary least squares was used. For further discussion of the model fitting process and regression techniques, please see Ref. 1.

For the specific purposes of this time trend assessment, we attempted to isolate the impact of time on instrument cost by removing ("modding-out") the impact of all other significant variables affecting cost. We then add a time variable to the model and study its impact and significance. The time variable we append to the model is based on the time of launch of the mission carrying the instrument, defined as the number of years between launch and 1980:

$$LYsince1980 = \text{Year of Launch} - 1980 \tag{4}$$

Other ways in which to define this variable were entertained, but were either equivalent to this definition for our purposes of regression or incompatible with the model (e.g. choice of the year 1980), or were not as simple to objectively define. For instance, the launch year was used in the definition (rather than, say, start of Phase B) since it is readily available data with a concrete meaning for all instruments throughout time.

Significance results can be sensitive to assumptions of normality and independence of variables used in the model. While these assumptions have not been rigorously tested at this point in the analysis, a signal-to-noise ratio (SNR) is used to gauge how sensitive our regression is to these assumptions:

$$SNR(\beta_i) = \frac{\mu_{\beta_i}}{\sigma_{\beta_i}} = \frac{t\text{-statistic}}{\sqrt{N-p}} \tag{5}$$

where N is the number of data points, p is the number of parameters used to fit the model, $\hat{\beta}_i$ is the fitted value for β_i, and $\widehat{se}_{\hat{\beta}_i}$ is the estimated standard error around $\hat{\beta}_i$. The t-statistic is used in the context of ordinary least squares regression, associated with the hypothesis $\beta_i = 0$, for some $i = 1, \ldots p$. When $SNR(\beta_i) < 1$, we note that our significance results for $\hat{\beta}_i$ are sensitive to normality and independence assumptions. For further discussion of this technique, see Ref. 2.

IV. Analysis of Time Trends for NASA Science Instruments

The analysis discussed above was carried out for each instrument type. Areas showing moderate to strong evidence of a time trend are discussed here and are recommended for further study (e.g. time series analysis). Areas not discussed either showed little evidence of a time impact, or showed some evidence, but lacked the statistical significance to pursue further. Table 1 summarizes the strength of evidence found for each instrument type.

Instrument Type	Evidence for Trend
Particles	Moderate to Strong
Optical, Planetary	Moderate to Strong
Microwave*	Little evidence
Fields	Little evidence
Optical, Earth Orbit	Little evidence

*Includes active & passive microwave instrument systems.

Table 1. Strength of Evidence for a Time Trend – by Instrument Type

A. Optical (Planetary) Instruments

Optical instruments with a "planetary" destination[4] show what may be a slight reduction in cost per kilogram over time. Figure 3 shows a box-whisker plot of historical dollar-per-kg for instruments of this type. There appears to be evidence that the dollar-per-kg for optical instruments has either stayed the same or come down slightly over the last 25-30 years.

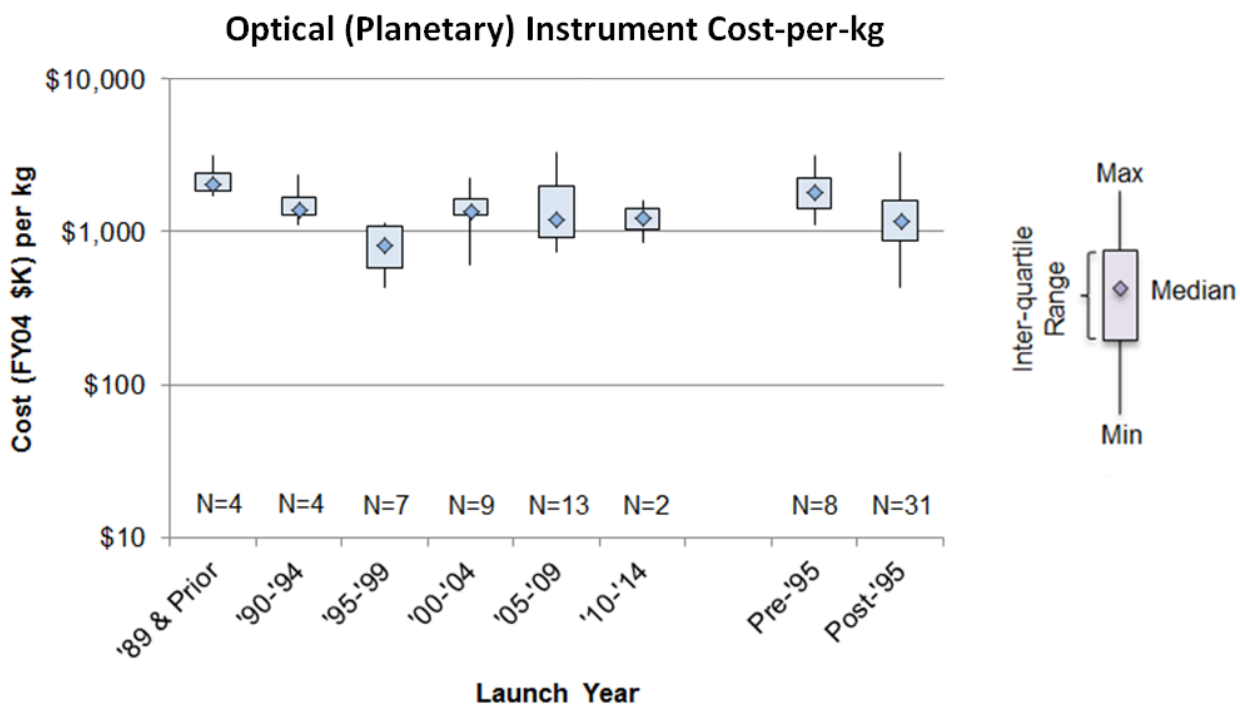

Figure 3. Optical (Planetary) Instruments dollar-per-kg Box-Whisker Plot – 5 Year Bins (left); Pre-1995, Post-1995 (right).

[4] The term "Destination" has two possible values in this analysis: Earth Orbiting or Planetary. "Earth orbiting" for purposes of this analysis, is defined as anything in a geocentric orbit. The term "Planetary" refers to anything that does not satisfy the definition of Earth orbiting.

Examining the trend more closely with our elasticity model provides evidence that this decrease in cost over time for optical planetary instruments is indeed significant. Figure 4 shows the result of a bootstrapped hypothesis test on the elasticity for the time variable "LYSince1980". The null hypothesis being tested is *H_0: LYSince1980 is independent of other variables in the model (implying that the elasticity on LYSince1980 is 0)*. The ninety-five percent confidence interval around this hypothesis is (-0.46, 0.44). Since the fitted value of -0.58 falls outside this range, the null hypothesis may be rejected and the result deemed significant. Note that $SNR = 0.4 < 1$. However, the bootstrap procedure applied here does not assume a distributional form, and the PCA regression technique used to fit the model helps untangle correlation amongst the variables included in the model. Therefore, these significance results may be more robust than other fitting methods (such as Ordinary Least Squares), but future work should verify this.

Discussion of these results with senior instrument developers is consistent with the observations of this analysis: There have been fewer mass-driven design constraints affecting optical instrument development and a greater number of suppliers in the market providing optics, which would drive costs down. The combination of these effects have tended to reduce the cost of optical instrument developments over the years. On the other hand, the data included instruments from NASA "flagship" missions, which tend to have more money available, in the earlier years, while the later years tended to be dominated by smaller missions, which would have been more budget constrained. Thus, the decrease in dollar-per-kg may be driven by the launch manifest, or order in which these missions where developed and launched. In other words, had the launch manifest been in a reverse order, would we have an observed an increasing effect rather than decreasing?

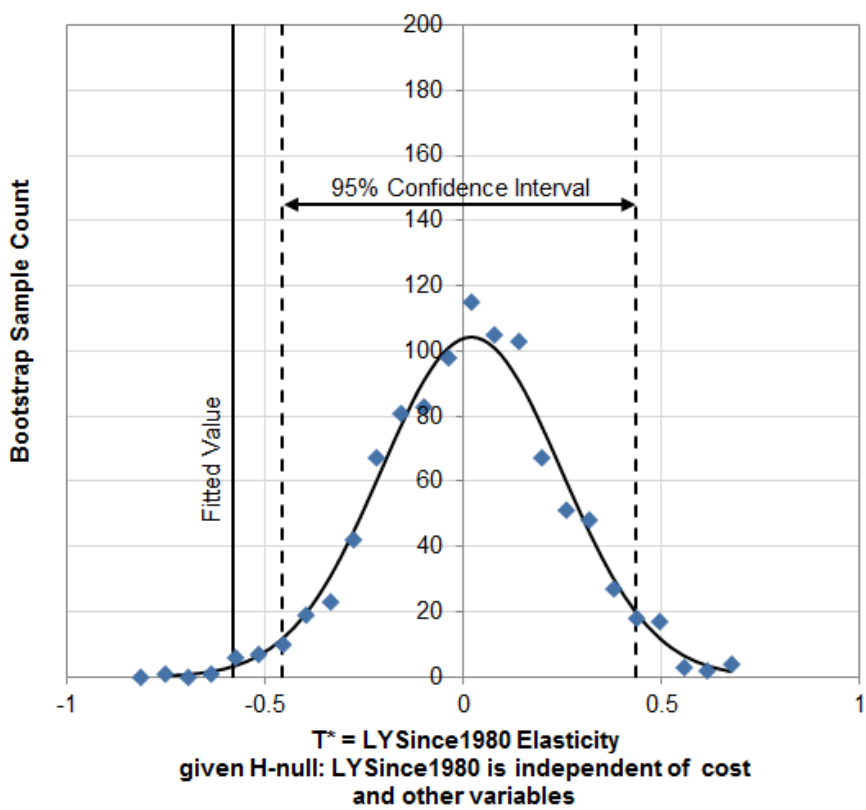

Figure 4. Bootstrap hypothesis test showing significance of a time-elasticity impact on optical (planetary) instrument cost. *The data set is bootstrapped under the hypothesis: "LYSince1980 is independent of other variables in the model" to give the distribution indicated by the blue diamonds and solid bell-shaped curve. An approximate 95% confidence interval (-0.46, 0.44) is shown by the vertical dashed lines. This shows the low probability (<1%) of observing a value less than or equal to the value fitted to the data (-0.58), if there were no relationship between time of launch and instrument cost. Hence the relationship between time of launch and instrument cost is deemed significant.*

B. Particles Instruments

Particles instruments show what may be a slight reduction in cost per kilogram over time. Figure 5 shows dollar-per-kg for Particles instruments. As was observed with optical (planetary) instruments, the box-whisker plot in Figure 5 shows evidence that the dollar-per-kg for particles instruments has either stayed the same or come down slightly over the last 25-30 years.

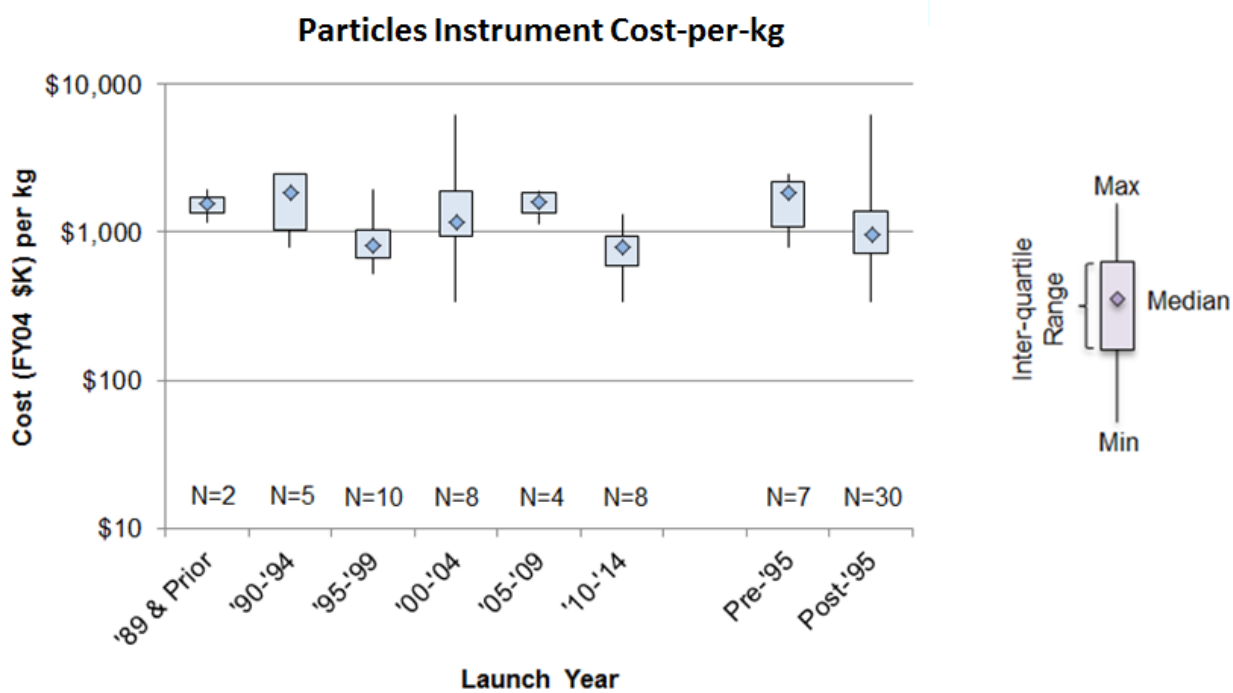

Figure 5. Particles Instruments dollar-per-kg Box-Whisker Plot – 5 Year Bins (left); Pre-1995, Post-1995 (right).

Examining the trend more closely with our elasticity model provides evidence that this decrease in cost over time is significant. Figure 6 shows the result of a bootstrapped hypothesis test on the elasticity for the time variable "LYSince1980". The null hypothesis being tested is H_0: *LYSince1980 is independent of other variables in the model (implying that the elasticity on LYSince1980 is 0)*. The ninety-five percent confidence interval around this hypothesis is (-0.47, 0.45). Since the fitted value of -0.61 falls outside this range, the null hypothesis may be rejected and the result deemed significant. Note that $SNR = 0.5 < 1$. As was the case for optical (planetary) instruments, these significance results may be more robust than other fitting methods, but future work should verify this. Moreover, further discussion with particles instrument developers is necessary to validate these trend observations. Note that the same launch manifest discussion made for optical (planetary) instruments may apply here as well for particles instruments.

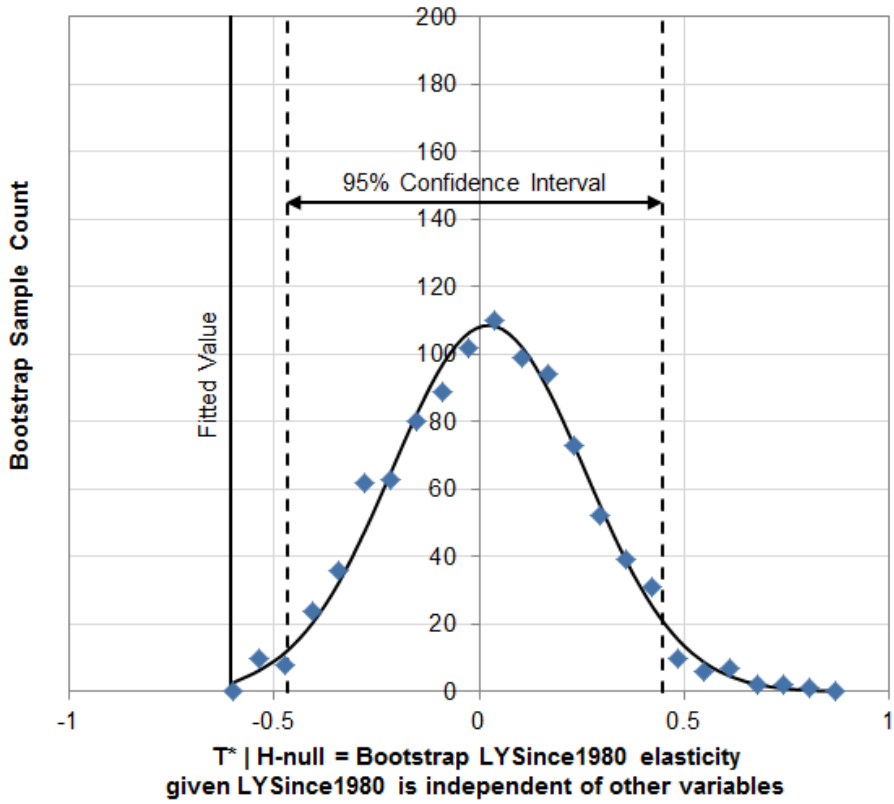

Figure 6. Bootstrap hypothesis test showing significance of a time-elasticity impact on particles instrument cost. *The data set is bootstrapped under the hypothesis: "LYSince1980 is independent of other variables in the model" to give the distribution indicated by the blue diamonds and solid bell-shaped curve. An approximate 95% confidence interval (-0.47, 0.45) is shown by the vertical dashed lines. This shows the low probability (<1%) of observing a value less than or equal to the value fitted to the data (-0.61), if there were no relationship between time of launch and instrument cost. Hence the relationship between time of launch and instrument cost is deemed significant.*

C. Microwave Instruments

The microwave instruments showed no downward trend upon visual inspection in the box and whisker plot (see Figure 7). A slight uptick is seen in the 2010-2014 region, which is responsible for the increase seen in the Post-'95 bin over the pre-'95 bin as well. The next five years of NASA Microwave instrument launches will illuminate whether a true upward cost trend is coming about.

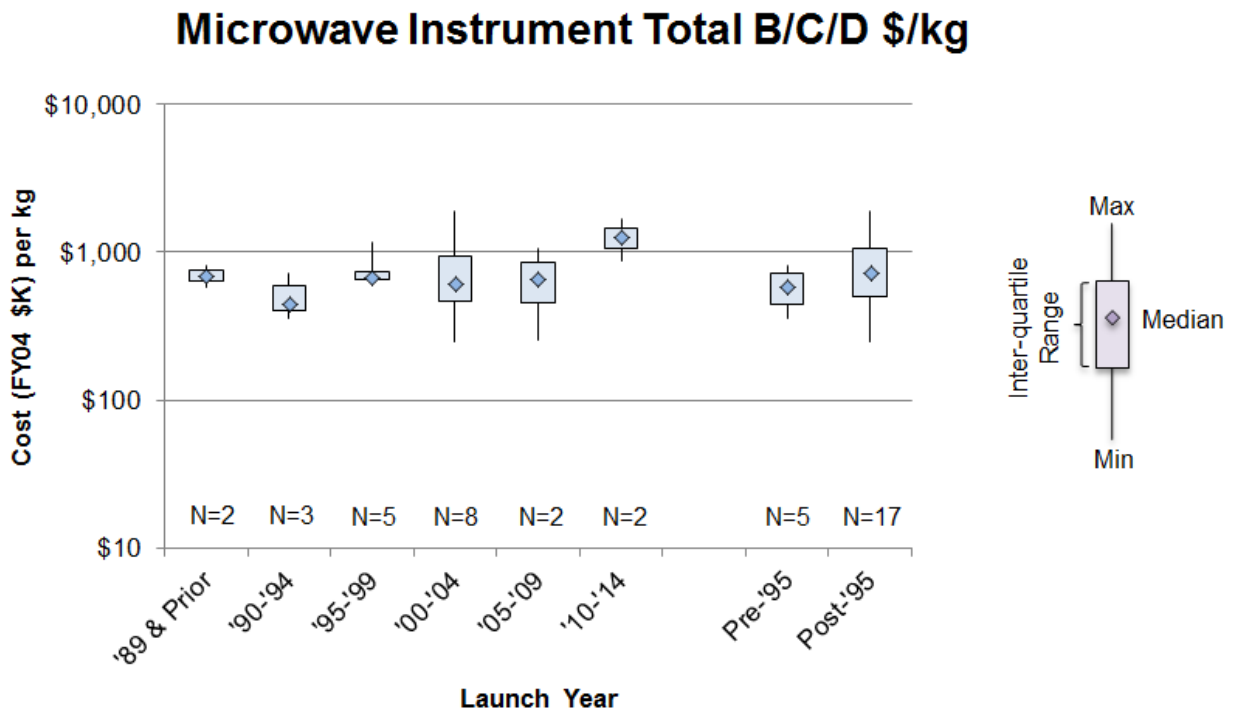

Figure 7. Microwave Instruments dollar-per-kg Box-Whisker Plot – 5 Year Bins (left); Pre-1995, Post-1995 (right).

D. Optical (Earth Orbiting) Instruments

The optical-Earth orbiting instruments showed no downward trend upon visual inspection in the box and whisker plot (see Figure 8). An uptick is seen again in the 2010-2014 region just as with the Microwave instruments. Again, the next five years of NASA optical Earth orbiting instrument launches will illuminate whether a true upward cost trend is coming about.

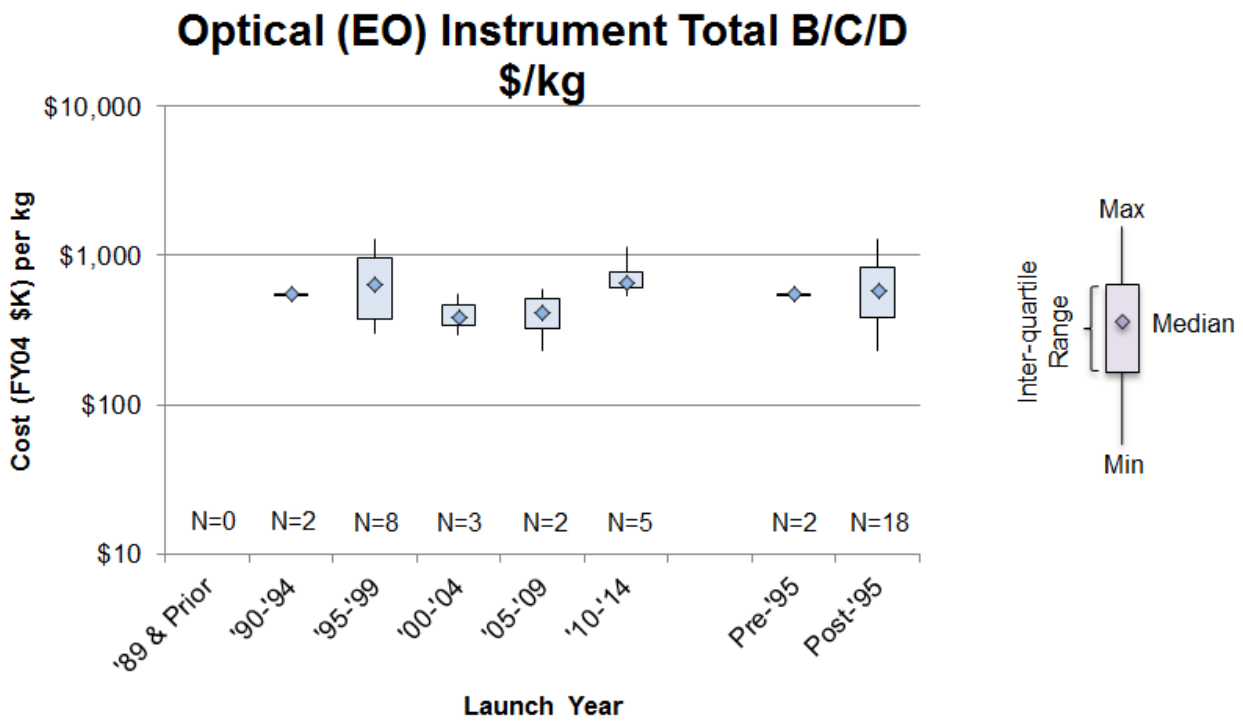

Figure 8. Microwave Instruments dollar-per-kg Box-Whisker Plot – 5 Year Bins (left); Pre-1995, Post-1995 (right).

E. Fields Instruments

The fields instruments data set was unfortunately too small to draw any meaningful conclusions (see Figure 9). Further data collection will be needed before revisiting cost trends for Fields instruments.

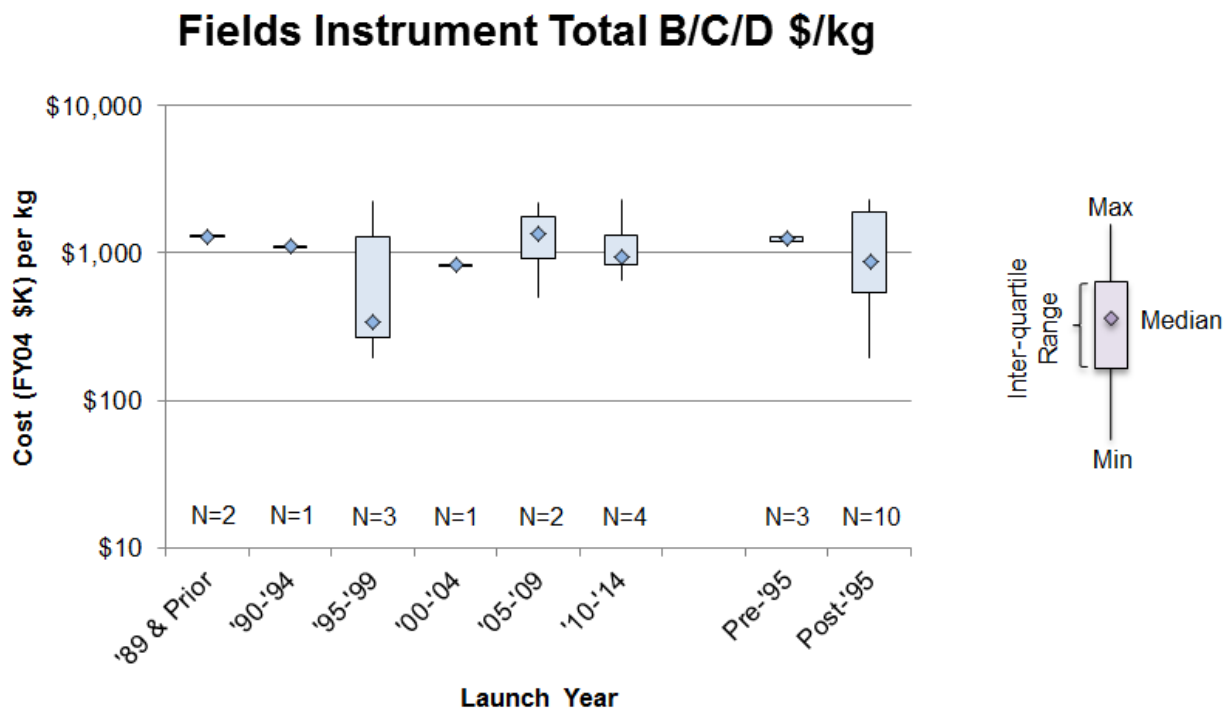

Figure 9. Fields Instruments dollar-per-kg Box-Whisker Plot – 5 Year Bins (left); Pre-1995, Post-1995 (right).

V. Conclusions and Further Discussion

We presented evidence in favor of a drop in the median dollar-per-kg value for Particles and Optical-Planetary instrument types. While similar evidence was weak at best for Fields and Microwave instruments. We can speculate as to the causes for this effect, but we are also equipped to begin to rule out, or at least prioritize, some of the suspected drivers. We observed, for Particles and Optical-Planetary instruments, that perhaps a launch manifest effect was playing part of the role in the observed decrease in dollar-per-kg over the years, noting that the more flagship class missions, which have more money to spend on their instruments, were seen in the earlier years in our data, versus the later years which were dominated by less expensive class missions. However, if this were a dominating driver, would we not have seen the downward trend in the Fields and Microwave instruments as well, which were drawn from that same launch manifest? The fact that we did not observe this helps us rule out the launch manifest effect, and other drivers, such as advances in technology, that seem to be more likely suspects. In that case, however, why would technology advances be helping the Particles and Optical-Planetary instruments only? Why would it not be impacting Optical-Earth Orbiting instruments? Further suspects were looked at as well and ruled out, such as the "Faster, Better, Cheaper"era of NASA development which did not seem to actually impact trends by instrument type on a dollar-per-kg scale.

VI. Future Work

A. Time Series Detailed Statistical Assessment

The analysis discussed above sets the foundation for a more rigorous time series analysis of the data. Time series analysis will further explore evidence to-date of time trends for the instrument types which showed the strongest indicators for a decrease in dollar-per-kg: Optical (Planetary) and Particles instruments. More than providing evidence and top-level significance tests, time series analysis would help elucidate what kind of trend that exists in the data, their significance and allow statistically based forecasting (see Figure 10).

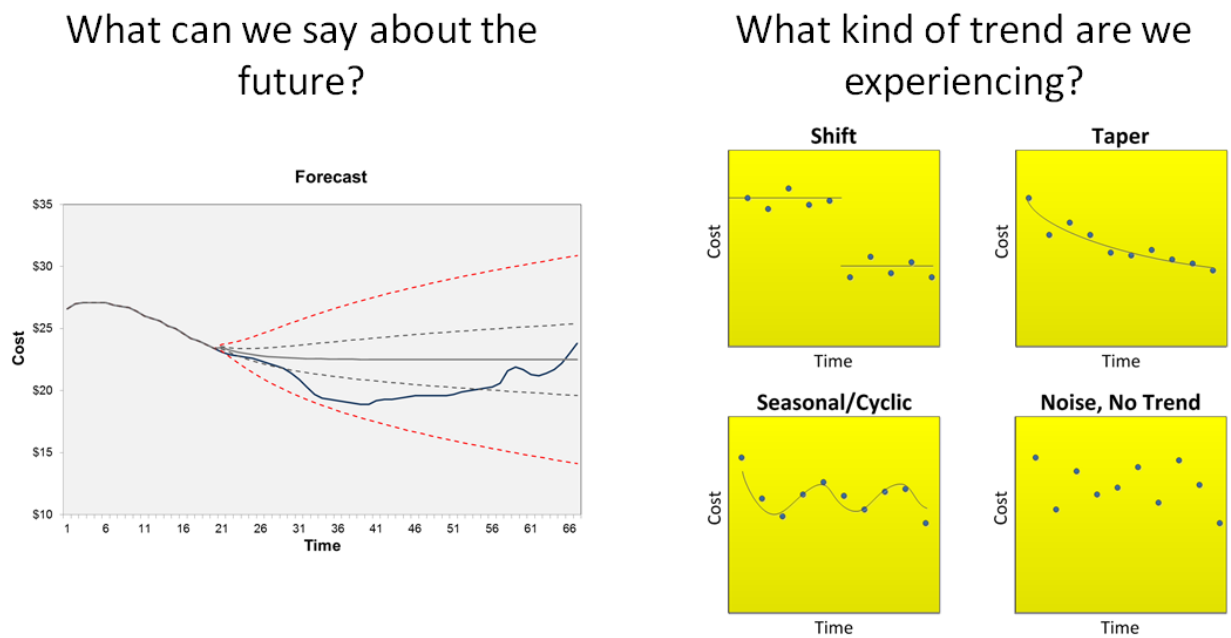

Figure 10. Time series analysis may enable statistical forecasting of future instrument costs (left) and would help elucidate the kind of time trend in the data (right): for example, a discrete shift from level to another; a taper over time; a seasonal/cyclic pattern; or something that cannot be differentiated from noise.

B. Instrument Subsystem Cost Trends

Intial work was completed to offer another perspective of interest to individual engineering disciplines by way of examining cost trends at the various instrument subsystem levels: detectors, optics, mechanical/structures, thermal, software, antennas and electronics. Visual indictor methods, as described earlier in this paper, show some evidence that the optics subsystem hardware, and the instrument software, are two instruments subsystems which may be showing a downward trend in cost as time progresses.

Acknowledgement

The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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References

[1]Habib-Agahi, H.,et. al., "NASA Instrument Cost Model (NICM) Version VII, Doc #982-0000 Rev. 7", Jet Propulsion Laboratory/California Institute of Technology (NASA sponsored), Pasadena, CA 91109, February 2016.

[2]Swan, Peter, "Doubtful Significance: Can an Amorphous Cloud of Points Really Illustrate a Significant Relationship?", Nottingham University of Business School Research Paper Series No. 2012-08, Version 1.2,August 2012.