NASA Technical Memorandum 83633

Determination of the Key Parameters Affecting Historic Communications Satellite Trends

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June 1984

NASA

DETERMINATION OF THE KEY PARAMETERS AFFECTING HISTORIC COMMUNICATIONS SATELLITE TRENDS

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E-2072

SUMMARY

Data representing 13 series of commercial communications satellites procured between 1968 and 1982 were analyzed to determine the factors that have contributed to the general reduction over time of the per circuit cost of communications satellites.

The model by which the data were analyzed was derived from a general telecommunications application and modified to be more directly applicable for communications satellites. In this model satellite mass, bandwidth-years, and technological change were the variable parameters. A linear, least squares, multiple regression routine was used to obtain the measures of significance of the model. Correlation was measured by coefficient of determination (R^2) and t-statistic.

The results showed that no correlation could be established with satellite mass. Bandwidth-year, however, did show a significant correlation. Technological change in the bandwidth-year case was a significant factor in the model.

This analysis and the conclusions derived are based on mature technologies, that is, satellite designs that are evolutions of earlier designs rather than the first of a new generation. The findings in this study, therefore, are appropriate to future satellites only if they are a continuation of design evolution.

INTRODUCTION

Geostationary communication satellites have now had 20 years of experimental and operational service. The progress in exploiting this means of communication has been remarkable by any measure. The number of transponders, the available bandwidth, and the number of voice circuits per spacecraft have increased dramatically during this time. So, too, have typical satellite sizes and costs. Data representing 13 commercial spacecraft series procured over 14 years, from 1968 to 1982, present an opportunity to determine significant trends as well as the key factors that relate spacecraft output (transponders, bandwidth, circuits) with size and cost.

Several attempts have been made to relate these factors. Martin (ref. 1) showed a trend of decreasing investment cost per satellite voice circuit per year for the period 1965 to 1979. Later, Lovell and Fordyce (ref. 2) used additional, more recent data to arrive at a parameter (on-orbit cost per channel-year or per transponder-year, depending on application) which served as a figure of merit to compare satellites. Both references showed a similar trend toward, decreasing cost parameter with time. As valid as these trends may be, neither source provided any insights into the relationships of the factors to each other.

Recent interest has been expressed by European researchers in satellite systems data so they might assess candidates for future European telecommunications efforts (refs. 3 to 5). They have used the data to determine cost elements based on mass. The exclusive attention devoted to mass, however, can lead to distorted conclusions. If the output (bandwidth, number of circuits, etc.) is proportionally greater than the increased mass or increased cost, the higher mass or cost could very well be acceptable. Not enough information was available in these references to make definite conclusions.

The above references indicate the need for identifying the significant factors in any assessment of satellite data and an understanding of the synergy involved. This study approached this task by

(1) Using a model that included all pertinent factors.

(2) A statistical analysis that weights the factors according to their relative significance.

ANALYSIS

The model used in this study was developed by Ellis (ref. 6). It is basically one used by econometricians but modified for telecommunications applications as follows:

$$C = ke^{-\psi(t - t_o)}X^aV^cD^d \tag{1}$$

where

C	cost
ψ	annual exponential rate of technological change
X	capacity
V	production
D	distance
$t - t_o$	time interval, in years, from first procurement, t_o
k,a,c,d	unspecified constants

The factors X, V, and D are the independent variables that include telecommuni- cations applications as diverse as submarine cables, data modems and computers. The exponents a, c, and d are the economies of scale ranging from zero to unity.

If these factors were to constitute all the influences on C, the model would be tacitly assuming a static technology. Ellis' use of the term ψ stems from Snow's (ref. 7) concept of technological progress. Snow asserts that there is a time trend of cost with technology quite apart from the scale economies due to the interactions of a and X, of c and V, and of d and D.

Ellis' model can be adapted for communications satellites with further modifications. Distance D is not a factor in communications by satellite and can be eliminated from consideration. Production V as applied to communications satellites, can also be ignored because (1) the number of satellites built for each series is limited compared with most production runs; and (2) in many cases the data for some satellites in a series are not applicable to others in the same series, thereby reducing the production run even further. Satcoms 1 and 2, for example, have a different per satellite cost, mass, bandwidth, and life from Satcom 4. Thus, in this analysis, Satcom 4 was regarded as being in a separate series from Satcoms 1 and 2.

The term X, capacity, is general enough to apply to several different parameters. Mass was chosen as one parameter because of its prevalent use in scaling calculations and other uses as mentioned in the Introduction. Satellite mass can be viewed as a physical measure of the satellite capacity. In contrast to this physical measure, bandwidth-years was chosen as a parameter to represent the functional measure of satellite capacity. "Bandwidth" as used in this report refers to the total bandwidth of the satellite. "Years" refers to the satellite design life. Bandwidth-years, then, is the total integrated capacity of the communications satellite. Equation (1) then reduces to

$$C = ke^{-\psi(t - t_o)}X^a \tag{2}$$

where C is the cost of a single satellite of a design series. If the equation is divided by X, the left side of the equation becomes cost per unit capacity per satellite. Substituting UC for C/X, $\Delta\tau$ for $t - t_o$, and $-n$ for $a - 1$, the equation becomes

$$UC = ke^{-\psi\Delta\tau}(X)^{-n} \tag{3}$$

The equation is in a form amenable to a statistical analysis. Historical satellite data provide the input for C, $\Delta\tau$, and X. Since X is defined both as satellite mass and as bandwidth-years, the analysis conducts two passes for each satellite. Of course, C and $\Delta\tau$ retain their individual satellite values for each pass. The results of the analysis provide a means of comparing the significance of satellite mass with the significance of bandwidth-years and to compare these parameters with technological change.

The data considered in this analysis are listed in table I. These commercial communications satellites include a wide range of designs spanning 14 years. Excluded were those satellites not considered to have achieved a relatively mature level of technology - such as Intelsats I, II, and III and SBS 1, 2, and 3. The SBS satellite series was designed with new technologies associated with an all digital 14/12 GHz system. The high cost of this system was judged to be associated with introducing a new technology; therefore, since comparison with the other technologically mature satellites could not be made on a consistent basis, SBS data were omitted.

The information source for the values given in table I are also cited. Much of the effort was directed at obtaining the cost figures. Most of the personal communications were based on eliciting the satellite procurement costs. These figures were then adjusted to 1982 dollars. The mass of the satellite is based on its value at the beginning of life (BOL). Life is the design life of the satellite.

The data were analyzed by initially transforming equation (3) into

$$\ln(UC) = \ln k - \psi\Delta\tau - n \ln X \tag{4}$$

Next, a linear, least squares, multiple regression routine was applied using the statistics software package, Minitab, written at Pennsylvania State University in 1981.

Measures of the significance of the model were the coefficient of determination, the coefficient of determination adjusted for the number of independent variables, and the t-statistic. The coefficient of determination R^2 is a measure of the correlation that can be explained by the linear relationship of the dependent and independent variables. The coefficient, however, does not differentiate between the total number of variables and those variables bound in an equation-type relationship. For example, if only three data points were available and the equation involves three variables, the solution involves matrix manipulation to arrive at the values of the unknowns, k, ψ, and n. There are no "extra" data points - degrees of freedom - that require a statistical approach to the problem. Where the number of data points is greater than the number of the variables in the equation, the number of degrees of freedom is the difference between the two. In the present case there are 13 data points and 3 variables, resulting in 10 degrees of freedom. Smaller coefficients of determination result when the analysis is conducted on 10 degrees of freedom instead of 13. The t-statistic is another statistical measure wherein the results show the relative importance of the variables involved; further, it accomplishes this based on a relatively small number (<30) of samples.

In summary, the analysis has the capability of indicating whether satellite mass or bandwidth-years is the more significant parameter defining X and whether either is more influential than technological change.

RESULTS

Regression analysis was conducted on equation (4) based on satellite mass X_m in one case and on bandwidth-years X_{B-Y} in the other. The computer program, Minitab, was used to solve the equation for the constants k, $-\psi$, and $-n$ on a least squares basis. The resulting equations were

$$UC_m = 0.165e^{-0.0069\Delta\tau}(X_m)^{-0.132} \tag{5}$$

where $UC_m = C/X_m$, and

$$UC_{B-Y} = 0.060e^{-0.0666\Delta\tau}(X_{B-Y})^{-0.195} \tag{6}$$

where $UC_{B-Y} = C/X_{B-Y}$. Measures of significance for these equations were also calculated by the program. These values are listed in table II.

The coefficient of determination R^2 is a measure of how well the data points define the least squares curve. Values of R^2 can range from 0 to 1, that is, from no correlation to a perfectly defined line, respectively. The value of R^2 was 0.101 for the satellite mass case (the -0.079 adjusted for the degrees of freedom indicates insignificance) and was 0.732 for the bandwidth-year case (0.678 adjusted for the degrees of freedom). These values indicate a sharp contrast between virtually no correlation on a mass basis and a significant one on a bandwidth-year basis. In a statistical sense, a coefficient of 0.70 is considered significant, though toward the minimum range of significance.

The contrast can be made apparent by plotting the left-hand sides of equations (5) and (6) on the ordinate and the right-hand sides of the equations on the abscissa. Ideally ($R^2 = 1$), the data points would fall directly on the least squares curve. In the satellite mass case (fig. 1) the data points define the curve very poorly. The pattern is very close to the classic $R^2 = 0$ case. For the bandwidth-year case (fig. 2) the data points fall into a clear linear pattern.

Additional graphs were plotted as part of the analysis - satellite cost per unit mass UC_m versus mass X_m in figure 3 and UC_m versus time interval $\Delta\tau$ in figure 4. The data points are widely dispersed and have poor correlation.

In contrast, the graphs plotted on the basis of bandwidth-years show good correlations. Figure 5 shows the relationship of satellite cost per unit bandwidth-year UC_{B-Y} versus bandwidth-year X_{B-Y}. Figure 6 shows UC_{B-Y} versus $\Delta\tau$. In both of these figures, the data points indicate a definite trend of decreasing UC_{B-Y} with increasing abscissa values. In reference 1 the plot of cost per transponder-year versus years (fig. 9 of the reference) shows a similar trend with time. Caution should be exercised in the interpretation of figure 5 for the Intelsat VI data point at 31 000 MHz-years. This cautionary note is issued from a purely statistical and graphical basis. The single point, by virtue of its extreme position, carries a much heavier influence than the other points in determining the results of the analysis. These remarks are not meant to indicate that the Intelsat VI vehicle should be treated analytically any differently from the other satellites.

In addition to the coefficient of determination, the t-statistic is an important measure of the significance of an independent variable in the model. The t-statistic is obtained from a (Student's t) distribution curve that is based on fewer data than those used to define a standard normal distribution curve. Texts tabulate t-statistics for data reaching up to 30 degrees of freedom. Since 10 degrees of freedom are involved herein, the t-statistic is considered to be a more accurate appraisal of deviation from the least squares curve.

The multiple regression routine produced a t-statistic number for each of the variables. The number itself must be referred to a standard student's distribution table to understand its significance. Procedurally, the t-statistic number is located in the table within the appropriate degrees of freedom category. This location identifies a confidence level which determines the degree of acceptability of the variable. Values of 95 percent are conventionally considered acceptable. If two variables are involved in the analysis, the variable with the higher t-statistic number is the more dominant factor.

Values of t-statistic are shown in table II. The negative signs are not relevant, just the absolute numbers. The t-statistic number of 2.51 for $\Delta\tau$ clearly establishes technological change as the dominant factor in the model based on bandwidth-years. Its confidence value is greater than 96 percent.

CONCLUSIONS

The applicability of the concept of economy of scale to communications satellites was analyzed based on a mathematical model relating satellite cost, capacity, and technological change. Data from 13 commercial, technologically mature, communications satellites were used to perform a regression analysis.

The analysis indicated that no economy of scale correlation could be established with satellite mass. On the other hand, the economy of scale based on bandwidth-year showed a significant correlation. Thus technological change was the significant factor in the equation using bandwidth-year as the capacity term.

A caveat should be observed. The data were subjected to a rigorous analysis but were chosen with a constraint. These satellites are not only the result of mature technologies, but they are the result of an evolution of designs, not radical departures from designs. Therefore, the relationships among the variables derived in this report would be applicable to future satellites only if the spacecraft are a continuation of a design evolution.

REFERENCES

1. Martin, James: Communication Satellite Systems. Prentice-Hall, 1978.

2. Lovell, R. R.; and Fordyce, S. W.: A Figure of Merit for Competing Communications Satellite Designs. Space Communication and Broadcasting, vol. 1, no. 1, Apr. 1983, pp. 53-63.

3. Vandenkerckkove, J. A.: The Effect of Scale on Satellite Costing. Advances in Earth Oriented Applications of Earth Technology, vol. 1, no. 4, 1982, pp. 251-260.

4. Kleinau, W.; Nauck, J.; Hansell, P.: Economy of Modularized Communication Platforms and Satellite Clusters. IAF Paper 82-224, Sept. 1982.

5. Molette, P.: Technical and Economical Comparison Between a Geostationary Space Platform and a Cluster of Satellites. IAF Paper 82-223, Sept. 1982.

6. Ellis, L. W.: Telecommunications' Declining Costs: Technology or Economies of Scale Electr. Commun., vol. 52, no. 3, 1977, pp. 180-186.

7. Snow, M. S.: Investment Cost Minimization for Communications Satellite Capacity: Refinement and Application of the Chenery-Manne-Srinivasan Model. Bell Journal of Economics, vol. 6, no. 2, Autumn 1975, pp. 621-643.

TABLE I. - DATA ON COMMERCIAL COMMUNICATIONS SATELLITES

Data points	Δτ, yr	Spacecraft name	Cost[a], $M	Mass, kg	Bandwidth, MHZ	Design life, yr	Bandwidth year	Information source
1	0	Intelsat IV	42.9	732	432	7	3 024	(b),(c)
2	4	Westar 1-3	25.5	297	432	7	3 024	(d),(c)
3	5	Comstar	42.9	790	864	7	6 048	(e),(c)
4	5	Intelsat-IVA	51.7	863	720	7	5 040	(b),(c)
5	5	Satcom 1,2	50.6	463	816	8	6 528	(f),(c)
6	8	Intelsat-V	62.4	1012	2000	7	14 000	(b),(c)
7	11	Satcom 4	34.1	573	864	10	8 640	(g)
8	12	Telstar 3A	49.1	659	816	10	8 160	(h),(c)
9	12	Westar 4,5	31.8	585	864	10	8 640	(d),(c)
10	13	Galaxy B	41.4	637	864	9	7 776	(i),(c)
11	13	G-Star	49.2	736	864	10	8 640	(j),(k),(c)
12	14	Intelsat-VI	133.0	1777	3100	10	31 000	(b),(c),(l)
13	14	Spacenet	30.0	660	1296	10	12 960	(m)

[a] Cost per satellite in 1982 dollars.
[b] "The Intelsat System" publication by Intelsat.
[c] "Future Connections" Table 1, published by NASA, vol. 1, no. 2, 1981.
[d] Hughes Fact Sheet.
[e] David Lee and Stan Rzewnicki, Comsat.
[f] RCA Astro Book.
[g] John Williamson and Dennis Eliot, RCA American.
[h] Bruce Andrews, AT & T.
[i] Cindi Sadler, Hughes Communications.
[j] J. Napoli, GTE.
[k] GTE Press Releases.
[l] Satellite Week, April 5, 1982.
[m] Dr. C. J. Waylan and Ron Dalebout, Southern Pacific Communications.

TABLE II. - SIGNIFICANCE OF DATA CORRELATION

Measure of significance	Model based on mass	Model based on bandwidth-years
Coefficient of determination, R^2	0.101	0.732
Coefficient of determination, adjusted for degrees of freedom	-.079	.678
t-statistic of X	-.78	-.98
t-statistic of $\Delta\tau$	-.46	-2.51

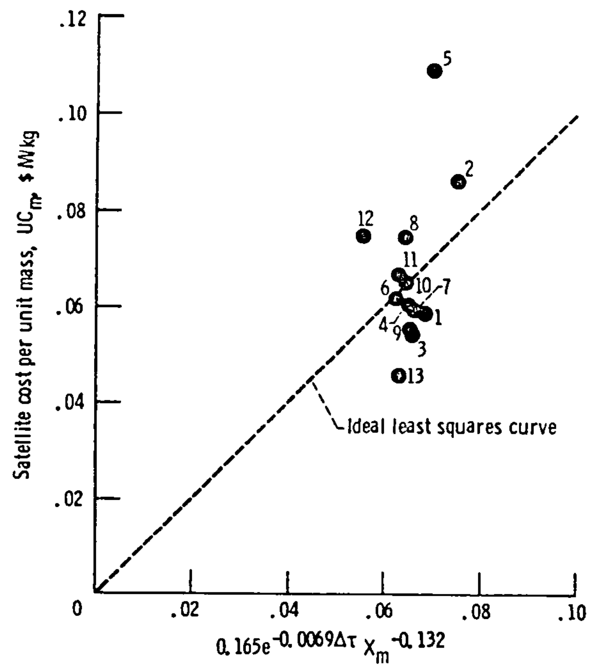

Figure 1. - Data plot based on satellite mass model equation (eq. (5)). Data points identified in table I.

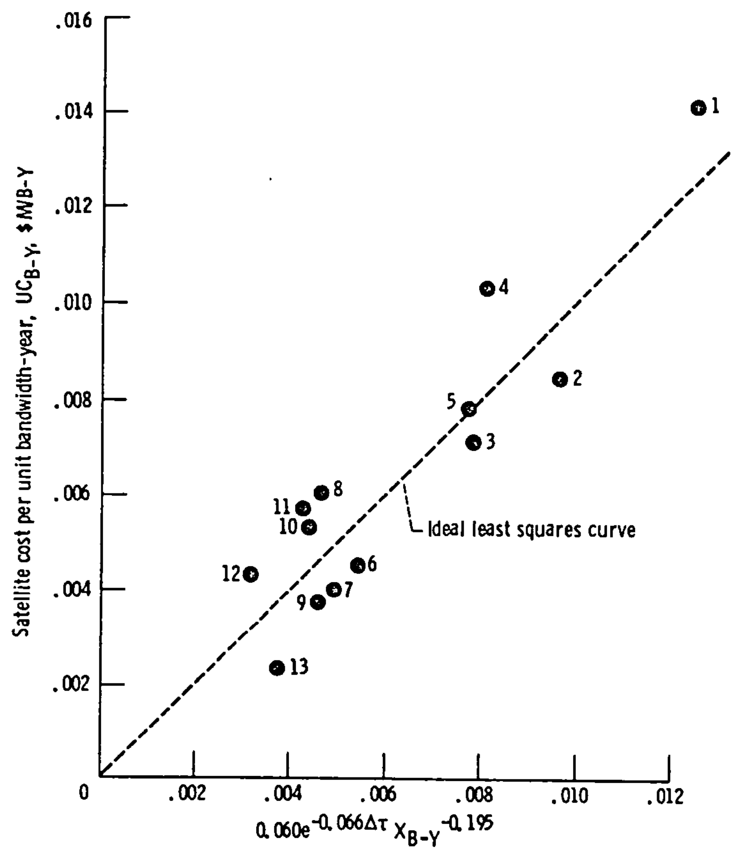

Figure 2. - Data plot based on bandwidth-years model equation (eq. (6)). Data points identified in table I.

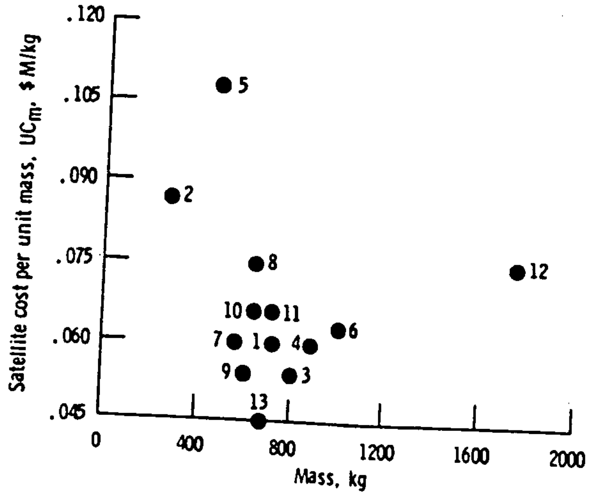

Figure 3. - Cost per unit mass as a function of mass. Data points identified in table I.

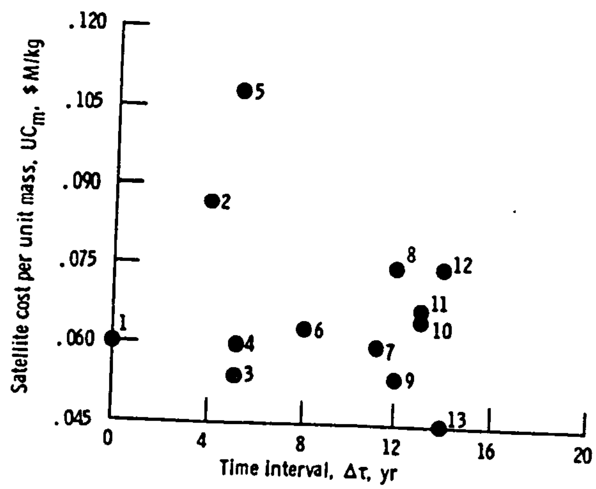

Figure 4. - Cost per unit mass as function of time interval (see eq. (11)). Data points identified in table I.

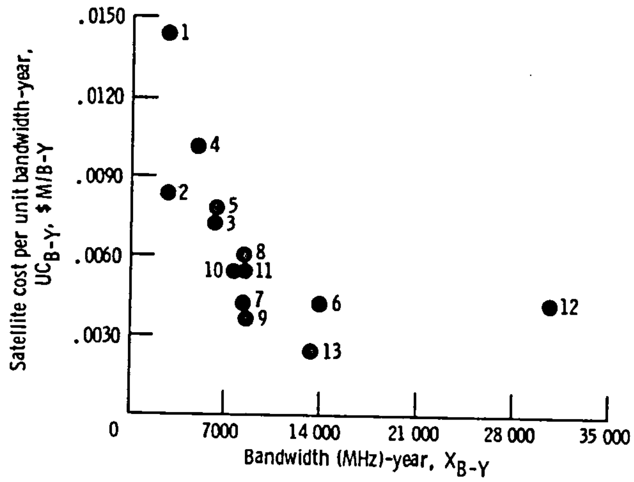

Figure 5. - Cost per unit bandwidth-year as function of bandwidth-year. Data points identified in table I.

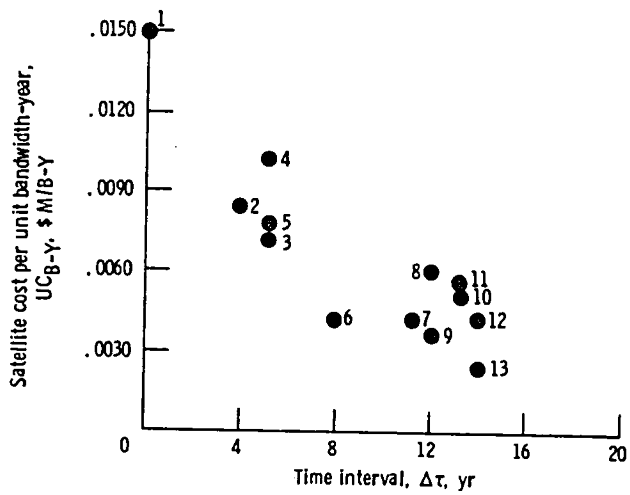

Figure 6. - Cost per bandwidth-year as function of time interval (see eq. (1)). Data points identified in table I.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-83633		

4. Title and Subtitle	5. Report Date
Determination of the Key Parameters Affecting Historic Communications Satellite Trends	April 1984
	6. Performing Organization Code: 650-60-26
7. Author(s): David Namkoong	8. Performing Organization Report No.: E-2072
	10. Work Unit No.
9. Performing Organization Name and Address: National Aeronautics and Space Administration, Lewis Research Center, Cleveland, Ohio 44135	11. Contract or Grant No.
	13. Type of Report and Period Covered: Technical Memorandum
12. Sponsoring Agency Name and Address: National Aeronautics and Space Administration, Washington, D. C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Data representing 13 series of commercial communications satellites procured between 1968 and 1982 were analyzed to determine the factors that have contributed to the general reduction over time of the per circuit cost of communications satellites. The model by which the data were analyzed was derived from a general telecommunications application and modified to be more directly applicable for communications satellites. In this model satellite mass, bandwidth-years, and technological change were the variable parameters. A linear, least squares, multiple regression routine was used to obtain the measure of significance of the model. Correlation was measured by coefficient of determination (R^2) and t-statistic. The results showed that no correlation could be established with satellite mass. Bandwidth-year however, did show a significant correlation. Technological change in the bandwidth-year case was a significant factor in the model. This analysis and the conclusions derived are based on mature technologies, i.e., satellite designs that are evolutions of earlier designs rather than the first of a new generation. The findings in this report, therefore, are appropriate to future satellites only if they are a continuation of design evolution.

17. Key Words (Suggested by Author(s))		18. Distribution Statement
Commercial	Historic	Unclassified - unlimited
Communications	Trends	STAR Category 32
Satellites	Statistical analysis	
Parameters		

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price*
Unclassified	Unclassified		

*For sale by the National Technical Information Service, Springfield, Virginia 22161

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