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EVALUATING SMALL SATELLITES: IS THE RISK WORTH IT?

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Abstract. "Faster, Better, Cheaper - pick any two" say critics of NASA's current approach to scientific satellites. As proof, they point to the recent failed or impaired small science satellites: Lewis (failed shortly after reaching orbit), Clark (cancelled before leaving the ground), NEAR (trajectory altered due to engine shutdown) and WIRE (failure resulting in depletion of cryogen). Although the space industry has greatly increased their utilization of small satellites to conduct space activities, the question remains, Is Faster, Better, Cheaper (FBC) yielding a good return on investment? This paper takes a historical look at traditional science missions either flown or started before the FBC era and compares them with missions designed under this new paradigm using a variety of metrics such as development time, cost per mission, and a newly proposed cost-effectiveness metric. Risk is discussd in terms of the failure rates (both catastrophic and partial) of both mission sets as well. Conclusions are reached on the relative merit of FBC and whether FBC is just a slogan or actually a new, valid approach for spacecraft design.

Introduction

Since becoming NASA Administrator in 1992 Dan Goldin has extolled the virtues of a Faster, Better, Cheaper (FBC) approach to scientific satellite missions. With nearly a decade of experience and close to two dozen scientific spacecraft flown, enough data are

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available to conduct an objective review of the FBC paradigm.

For the past three years, the authors have become familiar with FBC missions by participating in the proposal selection process for many of NASA's FBC programs. These programs, which include Discovery, Medium Explorer (MIDEX), Small Explorer (SMEX) and Earth Science System Pathfinder (ESSP), implement NASA's FBC approach by dictating both "faster" and "cheaper" by constraining schedule duration and available funding. While faster and cheaper can be imposed, "better" becomes the independent variable that is the primary question regarding the success of FBC.

This paper describes a review of the FBC approach through a comparison of traditional missions, either flown or conceived prior to the FBC era, with FBC missions initiated under the FBC paradigm. The purpose of the paper is to determine if FBC missions are, indeed, "faster, better and cheaper."

To perform this study, mission data was collected on NASA science mission launches over the past decade. The data collected and the mission selection criteria are further detailed in the Data Collection section. The database is provided as an Appendix with references to the source documents.

Several metrics were developed to assess FBC missions,. While "faster" and "cheaper" are relatively easy to measure, "better" is far more challenging. For this paper, "faster" is measured as reduced development time, "cheaper" is measured as reduced mission cost while "better" is measured using several metrics. Defining an objective measure of "better" is difficult but, for comparison purposes, this paper measures "better" by comparing flight rates (numbers of missions flown), failure rates (both catastrophic and partial) and performance according to a proposed science return metric developed specifically for this analysis. Overall science mission cost effectiveness is also investigated. In the sections that follow, the methods of data collection are summarized and a description of the results of applying the various metrics is provided.

Background

Several papers have been written evaluating "Faster, Better, Cheaper" [1], [2], [3], [4], [5]. The majority of these papers have provided a qualitative analysis of FBC only and have not dealt with a true quantification of the effectiveness of the FBC approach. This paper tries to quantify the overall effectiveness of FBC missions by using non-subjective metrics that utilize data found in the public domain.

The quantification of how much "better" a science mission may be is much less clear than the assessment of "faster" or "cheaper." For instance, how is the effectiveness of a science mission measured given that no two missions have the same fundamental objectives? Is a mission to Mars that completes 50% of its science objectives as effective as a simple earth-orbiter that completes 95% of its objectives? For example, what is the relative effectiveness of $2.0B Galileo mission compared to a $210M NEAR mission? Is it more effective to have a single, in-depth, large mission or a series of missions of more limited scope? Figure 1, as taken from NASA Administrator Dan Goldin's speech regarding the FY2000 NASA budget [6], tries to address the question of the effectiveness of one large Traditional mission versus several FBC missions using a simple comparison. This chart compares the relative expense of Galileo with eleven other small, FBC planetary missions. This chart does not imply that there is more scientific value in exploring the nearest planets vs. outer planets but it does suggest the greater variety of science afforded by the FBC approach. The effectiveness of one Galileo vs. eleven FBC missions has to be determined, in the end, by the science community.

Data Collection

Table 1 lists data parameters collected for this analysis. To isolate the impact of FBC on NASA, only NASA Science Missions that meet certain criteria were considered. Missions that have recently been launched, but have yet to begin their science missions (i.e. Cassini, Stardust, FUSE, QuickScat) were not considered because their success has yet to be determined. Missions that relied heavily on international contributions (i.e. TRMM) were eliminated from consideration due to the difficulty of assessing foreign costs. "Great Observatories", such as the Hubble Space Telescope and Compton Gamma Ray Observatory, were not considered in this comparison because the science objectives of these missions cannot be easily implemented using an FBC approach. Shuttle science experiments were not considered because they usually do not have funding, schedule and mass constraints that typify FBC programs. Technology demonstrators, such as DS-1, were also excluded given that their primary focus is technology demonstration, not science. DoD programs, such as the STEP and MSTI series of missions, were also not considered because our focus is on NASA missions. Clementine, although not strictly a NASA mission, has been incorporated in the database because it was one of the first examples of a FBC mission that had a strong NASA science component as well. The result is a set of 28 missions listed individually in the Appendix. All of the data collected, including the cost information, are from public sources. These sources include various editions of *Jane's Space Directory*, satellite
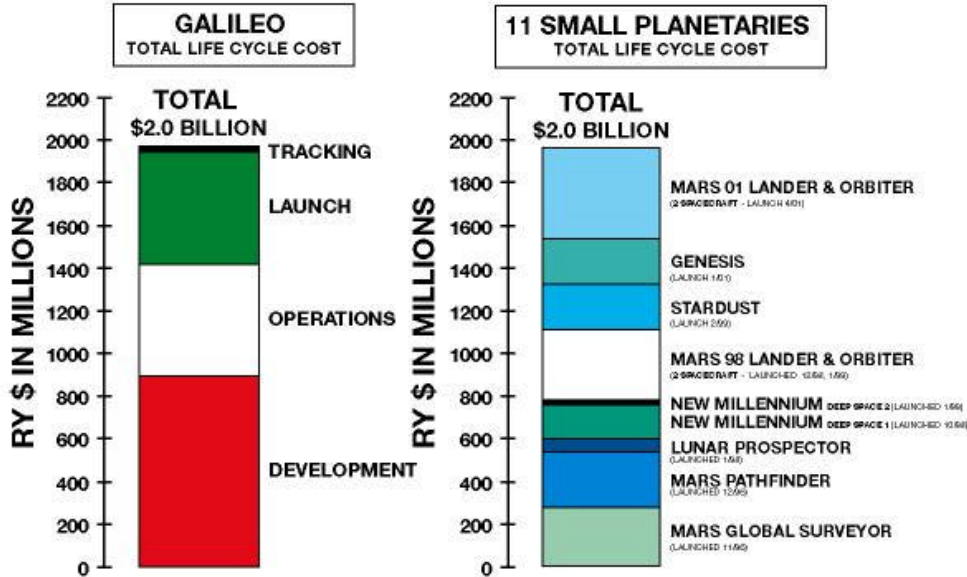
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Figure 1: Comparison of Galileo Cost with Eleven Small NASA Planetary Missions

Table 1: Science Spacecraft Mission Parameters

Parameter	Description
Mission Name	Name given to mission at time of launch. Some missions were renamed after launch, but can still be found under the listed mission name.

Mission Type	One of five types of science investigation missions:
	    1. Astronomy & Astrophysics
	    2. Space Physics
	    3. Planetary
	    4. Solar Physics
	    5. Earth Science

Launch Year	Year in which mission was launched.
Sponsor	Organization or organizations that oversaw development of mission.
S/C Contractor	Organization or organizations that oversaw construction of spacecraft.
Development Schedule	Length of time in years from contract award to launch (includes time awaiting launch, if applicable).
Instruments	Total number of instruments on spacecraft.
Launch Mass	Total wet mass of spacecraft.
Total Mission Cost	Total cost including the cost of the spacecraft, instruments, ground systems, launch vehicle and mission operations. Cost is normalized to FY98$ for comparison purposes.
Failure	Type of failure, catastrophic or partial, that occurred, if any, and the cause of the failure.
Mission Duration	Length of mission in years and length that instruments collected data, if different.

compilation websites, project websites, NASA press releases, *Florida Today* articles, and books from the Microcosm Space Technology Series. Detailed references for all the data can be found in the reference section.

The list of missions has been divided into "Traditional" and "FBC" missions. The Traditional missions considered were those that were initiated prior to the FBC paradigm that have been launched since 1989. The period beginning in 1989 was chosen due to lack of launches from 1986 to 1989 due to the Space Shuttle Challenger accident and the difficulty of finding reliable cost data on missions launched prior to 1986. The result is a set of ten Traditional missions that meet the described criteria. FBC missions are considered to begin with SAMPEX launched in 1992 and include all missions initiated under the FBC paradigm. The resulting 18 missions represent the FBC missions investigated for this paper.

A natural side effect of the FBC approach to robotic space science and exploration is that a fourth attribute, "smaller", could be added to the slogan. As shown in Table 2, the average and median launch mass for FBC missions has been reduced on the order of 85-90% compared to Traditional missions. Given the data, it is clear that a significant change has taken place in terms of design philosophy resulting in missions that have indeed become smaller in mass during the FBC era. Although this is a definite characteristic of the FBC approach, many caution that small spacecraft cannot and should not be the only tool for conducting space science. Some mission objectives, such as those required by the Great Observatories such as HST and Chandra, cannot be achieved in a small package. Also, flying fewer instruments on a single platform can lead to a reduced science benefit gained since data collected simultaneously from several instruments together on a single, larger platform can be used to create a richer scientific picture. Even with these cautions, however, it is clear that NASA using smaller spacecraft to implement their science missions and to achieve the goals of FBC.

Table 2: Traditional vs. FBC Launch Mass

Mission Class	Average (kg)	Median (kg)
Traditional	3013	2787
FBC	400	295

Results

Table 3 summarizes the various metrics that were analyzed for this paper. By design, the metrics are based on the database parameters, and can be directly related to one of the FBC standards.

Table 3: FBC Evaluation Metrics

Metric	Units	Measures
Development time	Years	Faster
Mission Cost	$K (FY98)	Cheaper
Flight Rate	Flights/yr	Better
Failure Rate	Percent	Better
Science Return	Instrument-months	Better

"Faster" Metrics

The metric used to assess "faster" is mission development time. An analysis of the data, as shown in Table 4, provides an indication that FBC missions are indeed faster. The data indicates that development time for FBC missions is approximately 40-50% less than Traditional missions.

Table 4: "Faster" Metric - Development Time

Mission Class	Average (Years)	Median (Years)
Traditional	7.1	6.0
FBC	3.6	3.5

As defined in Table 1, the definition of development time includes the period from contract award to launch. Launch vehicle delays, therefore, are included in the development times of these missions and have stretched these times to be greater than they would have been otherwise. Some Traditional programs were affected by the Space Shuttle Challenger accident (namely a 3 year delay for COBE) and the cancellation of the Centaur upper stage (1 year for both Galileo and Magellan). Similarly, launch delays associated with the Pegasus resulted in increased development times for FBC missions including HETE and FAST (1 year), TOMS-EP (2 years) and SWAS (3 years). The resulting development time without launch delay is shown in Table 5, and indicates that the FBC development times without launch delays are much closer to the commonly quoted goal of three years or less.

Table 5: "Faster" Metric – Without Launch Vehicle Delays

Mission Class	Average (Years)	Median (Years)
Traditional	6.6	6.0
FBC	3.25	3

"Cheaper" Metrics

Metrics of "cheaper", perhaps better phrased as "less costly", are fairly easy to generate. The fundamental question is whether FBC missions are, on average, less costly than Traditional missions. The quantitative measure used to assess this was total mission cost (TMC) as defined in Table 1. On the basis of the results from Table 6, FBC missions are on the order of 85% less costly than Traditional missions.

Table 6: "Cheaper" Metric – Total Mission Cost

Mission Class	Average (FY98$)	Median (FY98$)
Traditional	$654M	$483M
FBC	$96M	$65M

The role of inheritance in making FBC missions less costly should be mentioned. The design practices, testing techniques, knowledge of space environments, components and technologies inherited from Traditional missions allowed the FBC missions to selectively apply lessons learned to reduce cost to a minimum. Without the path blazed by Traditional missions, and the commercial space business that has grown from it, FBC missions could not be implemented with such a reduction in cost [5].

"Better" Metrics

There are numerous ways to define what it means for a mission to be "better." This paper attempts to measure "better" by several straightforward means: flight rates, failure rates, and a proposed metric that may indicate science return.

The first potential metric of "better" is the number of flights per year. More flights per year could represent a greater quantity and variety of science being conducted. Table 7 indicates that the FBC missions have realized a higher flight rate. Further, the forecasted annual flight rate of 5 or more flights per year for FBC missions for the year 2000 and beyond exceeds the average and median FBC value.

Table 7: "Better" Metric – Annual Flight Rate

Mission Class	Average (Years)	Median (Years)
Traditional	1.25	1.0
FBC	2.75	2.75

Failure rates were also used to gauge the relative effectiveness of FBC and Traditional missions. Failures are categorized as either partial, where the mission was impaired in some way, or catastrophic, where the mission was completely lost (or, as in the case of Clark, never realized). Investigating this metric, Traditional missions suffered only 1 catastrophic failure (Mars Observer) out of 10 missions, while the FBC missions suffered 5 such failures (HETE, Lewis, Clark, WIRE and TERRIERS) out of 18 missions. Traditional missions also suffered 2 partial failure (Galileo, UARS), while FBC missions experienced 3 partial failures (Clementine, Mars Global Surveyor and NEAR). Table 8 summarizes this data and indicates that FBC missions do have a higher failure rate and, therefore, are not "better" than Traditional missions in terms of percentage of failures.

Table 8: "Better" Metric – Failure Rate

Mission Class	Catastrophic Failure Rate	Total Failure Rate
Traditional	10%	30%
FBC	28%	44%

An aspect of the failure rate that must be considered is the magnitude of the loss of Traditional missions versus FBC missions. The greater cost of Traditional missions identifies one of the inherent risks of having few, very costly missions and putting all of NASA's "eggs in one basket." For example, the loss of Mars Observer is exacerbated by its relative expense of $942M (FY98$) as compared to a total cost of the combined catastrophic failures of HETE, Lewis, Clark, WIRE and TERRIERS at $215M (FY98$).

While flight rate and failure rate are easily quantified, the primary measure of "better" for a NASA science mission should relate to the science return of a mission. To assess the science return of Traditional and FBC missions, an objective measurement was sought. Initially a variety of different metrics were investigated. One proposed metric is the amount of data generated by a science mission. This assumes, however, that an instrument that collects significant amounts of data, such as Synthetic Aperture Radar (SAR), would be inherently more valuable than instruments that collect less data. A metric consisting of the number of complete images could be developed but would not be valid for a comparison to non-imaging instruments. Another metric might be the number of papers published by mission scientists. This metric, however, would favor large, prolific teams that publish multiple papers versus a small team that publish a few, very significant papers. Similarly, a metric based on the number of "significant" findings that resulted from

the mission would be difficult to use given that the term "significant" is very subjective and difficult to quantify. It has also been suggested that the science value of an instrument is proportional to its mass. This metric suggests, however, that planetary missions are inherently less valuable than Earth orbiting missions because planetary missions typically have much less payload mass due to the difficulty of getting its payload to its final destination.

To be as objective as possible, a metric was developed to quantify "science return" using inputs that are readily available in the public domain. The proposed metric uses the number of the instruments on-board the satellite multiplied by the length of time the instruments take data at their final destination and is measured in terms of "instrument-months." Multiplying by the duration that the instrument operates provides a surrogate for the quantity and depth of information gathered by the instrument. The proposed metric also accounts for mission failures because the failed mission's instrument duration of operation, and corresponding science return, is zero. A primary assumption of this metric is that all instruments provide equal science value. The rationale for this assumption is that each instrument is placed on board a satellite to achieve a specific scientific objective and that all scientific objectives are of equal value.

A misleading characteristic of the instrument-months metric is that it could identify a high science return for a mission that could simply fly a suite of small instruments without producing any real science value. This metric, if used as the only measure of science return, could result in a selection of this type of mission. NASA's current selection process, however, would prevent a selection of this type of mission. NASA's competitive science selection process uses a peer review board of scientists to select the most valuable science from all proposals submitted. Table 9 identifies that, of the most recent round of Discovery, MIDEX and SMEX proposals submitted, only the top 5% were selected for implementation. Given the number of proposals submitted and the thoroughness of the evaluation process, it is believed that the science of these missions is of the highest value.

Table 9: Typical FBC Program Selection Statistics

Program	Proposals Submitted	Contracts Awarded
Discovery	29	2
MIDEX	35	2
SMEX	52	2

Defining "better" in terms of instrument-months provides an interesting insight into Traditional missions. Traditional missions are characterized by having a large number of instruments that operate over a relatively long duration. A mission such as, the Upper Atmospheric Research Satellite (UARS) for example, carries 10 different instruments and has exceeded its design life of 3 years by entering into its 8th year of operation. Although one instrument, ISAMS, had a failure after 1 year in orbit and another, CLAES, depleted its coolant after two years in orbit, the remaining instruments continue to operate. The total science return to date from UARS would therefore be a total of 804 instrument-months (i.e. 96 months x 8 instruments + 12 months for ISAMS + 24 months for CLAES).

FBC missions, however, are characterized by smaller spacecraft with fewer instruments that operate for a shorter duration than Traditional missions. The Fast Auroral Snapshot Explorer (FAST), for example, had four instruments on board with an operational mission lifetime of 3 years. The total science return for FAST would therefore be 144 instrument-months or 18% of the science return of UARS.

When the Traditional missions are looked at as a whole, the science return per mission is substantially higher than the FBC missions, as shown in Table 10. For the Traditional missions, the science return value reaches a high with UARS and a low value of zero for Mars Observer due to its failure. The FBC missions reach a high with SAMPEX while the failures of HETE, Lewis, Clark, WIRE and TERRIERS all return a value of zero. Based on the results of this metric, Traditional missions provide more science return per mission than FBC missions.

Table 10: "Better" Metric – Instrument-Months

Mission Class	Average (Instrument-months)	Median (Instrument-months)
Traditional	305	324
FBC	79	42

Although the proposed metric indicates that FBC missions do not provide as much "science return" as Traditional missions, other intangible benefits of FBC missions cannot be quantified. For example, the introduction of multiple new suppliers has increased the competitiveness of the spacecraft industry and would have been difficult to achieve under the Traditional acquisition approach due to the risk of using a new supplier on a large, expensive

program. The flexibility provided by the ability to cancel programs in trouble, such as happened with Clark, would have been very difficult to achieve with Traditional program due to the sheer magnitude of the sunk cost of these programs. The ability to service several different science communities simultaneously with small FBC missions does not lead to the science "data gaps" experienced under the Traditional approach [7]. The ability to respond quickly to interesting scientific discoveries is also an intangible that is difficult to measure and could not be achieved by Traditional missions due to their long development times. Although not quantifiable, these intangibles do identify other, qualitative benefits of FBC missions.

Cost Effectiveness Metric

The results shown relative to the "faster", "better" and "cheaper" metrics are not entirely unanticipated. FBC missions should be "faster" and "cheaper" because NASA's FBC programs dictate the maximum funding and schedule restrictions that define "cheaper" and "faster." The reduced scope required to meet the funding and schedule guidelines reduce the science return of FBC missions, as indicated by the proposed instrument-months metric.

One question that could be raised, however, is: Are FBC missions more cost-effective? A stated goal of many of the FBC program implementations is to determine the best science value for the dollar spent [8]. Given that we have defined science return as instrument-months, it is a simple task to divide this science return by the total mission cost to determine the cost-effectiveness of each mission. This simple formula is shown in Equation 1.

$$SMCE = \frac{I \cdot t}{TMC} \qquad (1)$$

Defining the terms in Equation 1: SMCE is the Science Mission Cost-Effectiveness metric where I is the number of different instruments flown, t is the time (in months) that the instruments were operated, and TMC is the overall total mission cost. In essence, this metric measures the mission's "bang for the buck" or the amount of science gathered per unit dollar. Again this metric takes into account mission failures because failed missions have a time (t) value of zero making their respective SMCE value zero also.

To develop a SMCE figure for the two classes of missions, it was decided to investigate the whole of all the Traditional missions versus the whole of all FBC missions. This "mission class" SMCE figure is defined by Equation 2.

$$Class\ SMCE_1 = \frac{\sum\limits_{j=1}^{n} i_j \cdot t_j}{\sum\limits_{j=1}^{n} tmc_j} \qquad (2)$$

In Equation 2, the mission class SMCE is the mission class Science Mission Cost-Effectiveness metric where n is the number of missions, i_j is the number of instruments on the jth spacecraft, t_j is the number of months of instrument operation for the jth mission, and tmc_j is the total mission cost for the jth mission. The "mission class" SMCE is calculated in this manner to prevent the impact of having a single mission unfairly skew the comparison of results. Also, similar to the failure rate calculation shown earlier, the figure is used to assess all Traditional missions taken as a whole vs. all FBC missions taken as a whole.

Computing these values, the mission class SMCE for Traditional missions is 0.52 instrument-months/$M while the SMCE for FBC missions is 0.82 instrument-months/$M. The data presented indicates that FBC missions are approximately 57% more cost-effective than Traditional missions.

Reliability

Satellite failures, both catastrophic and partial, have been assessed for specific cause of failure. Four areas of consideration were used in classifying each failure; *design* related *launch vehicle* related, *program management* related, and *unknown*. Design related failures included both software and hardware related failures. Launch vehicle related failures were failures due to launch vehicle design causing satellite failure. Although all missions have program management concerns, missions cancelled primarily due to poor program management have also been included. Lastly, unknown failures are in which investigation is on going or evidence is inconclusive to determining exact reason for failure. Both traditional and FBC missions have been included. As shown in Table 11, design-related failures, hardware in particular, proved to be the largest contributing area of spacecraft failure. Many of the spacecraft failures could have been prevented with additional testing or simulation. Case studies have been provided giving detail into each spacecraft failure and possible cause.

Case Studies for Catastrophic Failures for FBC Missions

HETE, the High Energy Transient Experiment, launched on November 4, 1996 suffered catastrophic failure due to separation failure from the Pegasus XL

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Table 11: Causes of Spacecraft Failure

Cause of Failures	
Design	
Software	27%
Hardware	41%
Launch Vehicle	9%
Program Management	9%
Unknown	14%

third stage. Separation failure can be attributed to power loss in the transient bus of the Pegasus XL third stage [9]. This power loss caused failure of 3 pyrotechnic devices to ignite. HETE remained inside the canister of the Pegasus XL third stage and was unable to deploy solar arrays and lost power. Failure of the HETE mission can be attributed to launch vehicle failure rather than actual satellite failure.

Lewis was launched on August 23, 1997 and re-entered the atmosphere on September 28th due to catastrophic failure. The goal of Lewis, to demonstrate advanced science instruments and new technologies for measuring changes in topography, was never reached as the spacecraft entered a flat spin in orbit resulting in loss of power to the solar arrays and eventual battery power discharge. Ground controllers lost contact on August 26th. The attitude control system design had been adapted from a system used on the Total Ozone Mapping Spectrometer spacecraft. Investigation into the attitude control system found that insufficient analysis had been done to adapt this design to a different spacecraft spin-axis orientation [10], [11]. Lack of knowledge about the behavior of the spacecraft in orbit resulted in rotational perturbations, which eventually led to an uncontrolled spin. Lewis mission failure could be attributed to design error.

The **Clark** spacecraft never made it to launch due to cancellation of the program in February 1998. The primary goal of Clark was to produce black and white stereo images with resolution up to 3 m. Primary reasons for cancellation of the program can be attributed to a combination of concerns about cost overruns, payload health, and an uncertain launch schedule. Projection of cost to complete the mission showed a cost overrun of 15 percent. To date, NASA had spent $55 million for the budgeted $49 million mission [12]. The instrument to be used on Clark had been sitting on the ground longer than had been expected, leading to reservations about its operation and health while in orbit. Lastly, the scheduling conflicts for Lockheed Martin Athena program resulted in further postponement of the mission. Many of the concerns leading to the

cancellation of the Clark mission related to top-level requirements for the mission. These top-level requirements have been captured in the area of program management.

WIRE, the Wide-Field Infrared Explorer, launched on March 4, 1999 suffered catastrophic failure due to design error and analysis. Known characteristics about a component in the instrument electronic box were not considered in depth, leading to an electrical power surge reaching the explosive devices at startup [13]. The activation of the pyrotechnics resulted in premature ejection of the telescope's cover resulting in exposure of the frozen hydrogen (used as a coolant) and the telescopes infrared detectors to the sun. As the telescope heated, the hydrogen converted to gas and expelled entirely within a period of 48 hours from launch. Without the necessary cooling, the scientific mission was considered a loss. Further testing and simulation may have resolved these problems before they occurred. In this instance, the WIRE mission failure could be attributed to design error.

TERRIERS, the Tomographic Experiment using Radiative Recombinative Ionospheric EUV and Radio Sources satellite, built under the NASA Student Explorer Demonstration Initiative (STEDI), launched on May 18, 1999. An orientation problem with the spacecraft to allow the solar arrays full exposure to the sun has resulted in battery discharge [14]. The orientation error could be attributed to possible errors in the attitude control system software. Although the spacecraft maybe recoverable at a later date, it is considered at this time to be a catastrophic failure. Since further testing and simulation may have prevented this occurrence, the TERRIERS mission failure could be attributed to design error.

Case Studies for Partial Failures for FBC Missions

Clementine was launched on January 25, 1994 aboard a Titan IIG. Clementine's objective included investigating the long-term effects of the space environment on sensors and spacecraft, and to make scientific observations of the Moon and the near-Earth asteroid 1620 Geographos. After completion of the lunar mapping, Clementine's on board computer malfunctioned on departure from lunar orbit. The malfunction caused a misfiring of several thrusters and total depletion of the fuel onboard [15]. The asteroid portion of the mission was cancelled. Testing of long term effects in the space environment were continued to the end of mission in a geocentric orbit. Partial failure of the Clementine mission could be attributed to design

error, although information as to whether this is software or hardware related has not been determined at this time.

NEAR, the Near-Earth Asteroid Rendezvous, was launched on February 17, 1996. Primary objective for the NEAR mission included orbiting the asteroid 433 Eros in January 1999. Due to a burn abort that occurred in December 1998, the NEAR will rendezvous with Eros over a year later in February 2000. The spacecraft aborted the scheduled engine burn after the onboard system safety limits set had been reached [16]. Reprogramming of these limits was done and a re-scheduled burn occurred on January 3, 1999. Further testing and simulation of the scheduled burn could potentially have solved this problem. In this instance, NEAR partial mission failure could be attributed to design error.

MGS, Mars Global Surveyor launched in November 7, 1996. One of the unique characteristics of this mission included using aerobraking to lower the orbit of the spacecraft. Flight controllers discovered a fault in the deployment of one of the solar array panels due to a damper failure [17]. This resulted in a revised and less rigorous aerobraking schedule. Now currently in orbit around Mars, MGS has experienced problems with the high gain steerable antenna [18]. The antenna is now in a fixed position in the azimuth negative direction and investigation is under way to determine why the antenna will not move [19]. Mechanism failure with a loose bolt located at the stuck position could be a possible cause for the lack of movement in the antenna. The lack of a steerable antenna will be apparent when the geometry between Earth and Mars will become unfavorable. Failure on the hinge for the solar panel could be attributed to hardware design and testing. The steerable antenna situation cannot be attributed at this point to a given category until further investigation is completed.

Case Studies for Partial Failure for Traditional Missions

Galileo was launched in October 1989. Primary objective to perform an in-depth study of Jupiter and surroundings. In 1991, commands were sent to the spacecraft to open the high gain antenna. During deployment, the antenna got stuck and remained in a partial open configuration. After a detailed investigation, a possible conclusion leading to the excessive friction on deployment was caused during shipment of the spacecraft [20]. Shipping vibrations can reduce the effectiveness of dry coatings and lubricant. Ground testing simulating shipment loads could possibly have shown excessive wear before launch. Since the evidence in this investigation is inconclusive, the failure is considered unknown.

UARS, Upper Atmosphere Research Satellite was launched on 12 September 1991 to perform an in-depth study into changes in the Earth's upper atmosphere. A total of ten instruments were included on the UARS mission, nine primary instruments and one mission of opportunity, the Active Cavity Radiometer Irradiance Monitor II (ACRIM II). A series of problems have reduced the original mission requirements beginning with a problem with a solar array clutch, which halted full science operations between 2 June 1992 - 20 July 1992 [21]. Also in mid-1992, failure of a chopper wheel drive system, resulting in failure of the Improved Stratospheric and Mesospheric Sounder (ISAMS) instrument. In April 1993, the radiometer measuring water vapor on the Microwave Limb Sounder (MLS) failed. Also the vertical scanning activator showed degradation in capabilities in 1994. Since most of the instruments were originally functioning, this would lead one to conclude failure in hardware design leading to partial failure of the mission.

Case Studies for Catastrophic Failure for Traditional Missions

Mars Observer was launched on September 25, 1992 on board a Titan III rocket. Shortly after reaching Mars orbit, the spacecraft was lost. Several possible reasons for loss of spacecraft have been proposed [22]. The primary conclusion was a rupture of the fuel pressurization side of the spacecraft. This resulted in loss of propellant putting the spacecraft into a spin. This high spin effect subsequently put the spacecraft into "contingency mode" disrupting the command sequence to turn on the transmitter. Additional causes included a power short circuit, and over pressurization of the NTO tank due to pressure regulator failure. The rupture of the pressurization side has been attributed to inadvertent mixing of fuel and oxidizer during the helium pressurization. In this instance, catastrophic failure can be attributed to hardware design error.

Cost-Effectiveness of Reducing Failures

In terms of the proposed SMCE metric, it has been shown that the FBC missions, even with the series of recent failures, provides a higher SCME than that experienced by Traditional missions. Nevertheless, a reduced failure rate for FBC missions would increase the achievable science return. If the cost required to reduce the number of failures is substantial, however, the SMCE metric of FBC missions could be reduced.

It can be hypothesized that increased mission expenditures could reduce the number of failures of FBC missions. For example, for those missions in which a design error resulted in mission failure, an extended development schedule or increased staffing may have caught these items before failure. Failures due to poor design or component or subsystem problems could have been caught with an increased level of testing or increased oversight. Mission failures arising solely from component failures could have been avoided by using more costly, S-class components or by increasing the redundancy of the system. Additional expenditures could also be used to acquire a more reliable launch vehicle as well. It could be argued that, given enough time and money, all of the failures that FBC mission have experienced could have been eliminated by spending more money. At what point, however, does the increased expenditure focused at reducing failures actually decrease the cost-effectiveness of FBC missions?

Given the data collected for this paper, a "break-even point" can be calculated where further expenditures focused at reducing failures would decrease the cost-effectiveness of the FBC missions. As stated previously, the realized SMCE of the FBC missions, including the failed FBC missions, is 0.82 instrument-months per $1M total mission cost. The maximum theoretical SMCE that the FBC missions could have experienced, assuming that all FBC missions were successful, is 0.97 instrument-months/$M. To calculate the SMCE "break-even point", a simple ratio of the maximum theoretical SMCE to the realized SMCE can calculate the percentage increase in total mission cost that, beyond which, the cost-effectiveness of the FBC missions begins to decline. Using the data collected for this paper, this "break-even point" is calculated at a value of 18%. Simply put, increased expenditures focused at eliminating failures would increase the cost-effectiveness of the FBC missions if the increased mission cost to catch or avoid all failures is less than 18%. If the cost to catch or avoid all failures is greater than 18%, the cost-effectiveness of all FBC missions would decrease. This simple ratio assumes that cost would have to be increased across all missions at an equal rate to catch potential failures given that each mission could not anticipate, a priori, where to focus additional spending to ensure a successful mission.

Conclusions

The purpose of this paper was to assess the relative merit of FBC missions compared to historical, traditional NASA missions. A variety of metrics were evaluated to determine if FBC missions

are truly faster, better and cheaper than their Traditional counterparts.

Are FBC missions faster? Yes. The data indicates that the average development time for FBC missions has decreased approximately 40-50% compared to Traditional missions. Of the FBC missions investigated, all were developed in less time than the average Traditional mission of 7.1 years.

Are FBC missions cheaper? Yes. The data indicates that the average mission cost for FBC missions has decreased approximately 85% compared to Traditional missions. Of the FBC missions investigated, all were developed at less cost than the average total mission cost of Traditional missions of $654M.

Are FBC missions better? Yes and no. The data indicates that, while average launch rate is higher for FBC missions, the average failure rate is also higher. The proposed science return measure also indicates that the Traditional missions have a greater science return. Given the reduced science return and higher failure rate of FBC missions, FBC missions cannot be considered "better." Based on the data gathered for this evaluation, the saying of "Faster, Better, Cheaper – pick any two" is true only if "faster" and "cheaper" are chosen. The data shows that to achieve faster and cheaper, the mission must give up "better" by reducing scope and science return on a per mission basis.

In an effort to roll all terms into a defining cost-effectiveness metric, the proposed science return metric was divided by the total mission cost to determine the science "bang for the buck." The data indicates that the mission class Science Mission Cost-Effectiveness (SMCE) for FBC missions is 74% higher than for Traditional missions. Although SMCE is a relatively simple metric, it does indicate a relative cost-effectiveness improvement of FBC missions over Traditional missions.

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Appendix

Mission Name	Mission Type	Lauch Year	Sponsor	S/C Contractor	Development Schedule (years)
Galileo	Planetary	1989	NASA, JPL	JPL, Ames	11
Magellan	Planetary	1989	NASA, JPL	Martin Marietta	7
COBE	Astronomy & Astrophysics	1989	NASA	GSFC, Ball	12
UARS	Earth Science	1991	NASA, GSFC	GE Astro Space, Farichild	6
Mars Observer	Planetary	1992	NASA, JPL	GE Astro Space	6
EUVE	Astronomy & Astrophysics	1992	GSFC, U of Ca Space Sciences Lab	GSFC, Fairchild	6
TOPEX/Poseiden	Earth Science	1992	NASA, JPL, CNES	JPL, Fairchild, Alcatel	5
Wind	Space Physics	1994	NASA, GSFC	Martin Marietta	6
XTE	Astronomy & Astrophysics	1995	NASA	GSFC	4
Polar	Space Physics	1996	NASA, GSFC	Lockheed-Martin	8
SAMPEX	Space Physics	1992	NASA	GSFC	3
Clementine	Planetary	1994	NASA, BMDO	NRL, LLNL	1.5
Mars Global Surveyor	Planetary	1996	NASA	Martin Marietta	1.5
Mars Pathfinder	Planetary	1996	NASA, JPL	JPL	3
NEAR	Planetary	1996	NASA	JHU/APL	4
HETE	Astronomy & Astrophysics	1996	MIT Center for Space Research	AeroAstro, LLC	6
FAST	Space Physics	1996	NASA, GSFC	GSFC	4
TOMS-EP	Earth Science	1996	NASA, GSFC	TRW, Perkin Elmer	5
ACE	Space Physics	1997	GSFC, CalTech	JHU/APL	4
SeaStar/Orbview 2	Earth Science	1997	NASA	OSC, Hughes	6
Lewis	Earth Science	1997	NASA	TRW	3
Clark	Earth Science	1998	NASA	CTA, Martin Marietta	4
Lunar Prospector	Planetary	1998	NASA	Lockheed	2.5
TRACE	Solar Physics	1998	Stanford	Lockheed Martin	2
SNOE	Space Physics	1998	GSFC	LASP	3
SWAS	Astronomy & Astrophysics	1998	NASA	GSFC	7
WIRE	Astronomy & Astrophysics	1999	NASA, JPL	GSFC	2
TERRRIERS	Space Physics	1999	BU Center for Space Physics	AeroAstro, LLC	4

Mission Name	# of Instruments	Launch Mass (kg)	Total Mission Cost (FY98$M)	Failure* Catastrophic	Partial	Mission Duration (months) Instrument	Total	Refs
Galileo	15	3881	2036.57	n	y,1	48	96	20,21,30
Magellan	1	3444	730.08	n	n	48	60	20,21,30,43
COBE	3	2265	304.75	n	n	10	12	20,21,30
UARS	10	6795	921.06	n	y,2	96	96	20,21,24,41
Mars Observer	7	2573	941.68	y,3	n	0	12	20,21,22,25
EUVE	4	3275	407.40	n	n	96	96	20,42
TOPEX/Poseiden	5	2402	558.72	n	n	96	96	20,24,46
Wind	8	1195	187.36	n	n	36	36	20,24,44
XTE	3	3000	203.07	n	n	24	24	23,24,26,31,40,45
Polar	12	1300	245.14	n	n	36	36	20,25
SAMPEX	4	258	76.67	n	n	84	84	20,21,27,31,41
Clementine	11	424	89.76	n	y,4	2	7	20,25,37,42
Mars Global Surveyor	6	651	281.09	n	y,5,6	24	72	18,20,33,42,46
Mars Pathfinder	3	890	273.98	n	n	4	10	26,47
NEAR	6	818	216.30	n	y,7	24	48	16,20,21,25,38
HETE	6	128	31.79	7,8	n	0	0	9,20,21,37
FAST	4	420.5	61.80	n	n	36	36	20,21,25,27,41
TOMS-EP	1	248	111.24	n	n	36	36	20,31,42,46
ACE	10	785	164.59	n	n	24	24	21,29,32,48,49
SeaStar/Orbview 2	1	309	43.69	n	n	120	120	20,24,25,42
Lewis	3	385	66.04	y,9	n	0	0	10,20,24,25,39,42
Clark	4	---	55.00	y,10	n	0	0	12,20,42
Lunar Prospector	6	295	68.68	n	n	18	18	20,23,25
TRACE	1	250	49.00	n	n	15	15	21,26,28,34,41
SNOE	3	132	12.00	n	n	18	18	24,25,42,50
SWAS	2	288	64.00	n	n	24	24	21,25,27,36,41
WIRE	1	250	50.00	y,11	n	0	0	20,23,31,36,37,45
TERRRIERS	9	272	12.30	y,12	n	0	0	20,24,28,35,42

*Failure Type

1. Antenna deployment
2. Multiple component failure
3. Propulsion component failure
4. Computer malfunction
5. Array stuck on deployment
6. Lack of antenna movement
7. Software related
8. Pegasus failure
9. ACS error
10. Project cancelled due to cost overrruns
11. Electrical power surge causing premature deployment of telescope cover
12. Unable to orient to sun