The Value of Information: A Background Paper on Measuring the Contribution of Space-Derived Earth Science Data to National Resource Management

Molly K. Macauley

May 2005 • Discussion Paper 05–26

RESOURCES FOR THE FUTURE

Resources for the Future
1616 P Street, NW
Washington, D.C. 20036
Telephone: 202–328–5000
Fax: 202–939–3460
Internet: http://www.rff.org

The Value of Information: A Background Paper on Measuring the Contribution of Space-Derived Earth Science Data to National Resource Management

Molly K. Macauley

Abstract

This study, prepared at the request of the Office of Earth Science at the U.S. National Aeronautics and Space Administration (NASA), describes a general framework for conceptualizing the value of information and illustrates how the framework might be used to value information from earth science data collected from space. The framework serves two purposes. One purpose is provision of a common basis by which to conduct and evaluate studies of the value of earth science information that serves a variety of uses, from improving environmental quality to protecting public health and safety. The second purpose is to better inform decisionmakers about the value of data and information. Decisionmakers comprise three communities: consumers and producers of information, public officials whose job is to fund productive investment in data acquisition and information development (including sensors and other hardware, algorithm design and software tools, and a trained labor force), and the public at large.

Key Words: Value of information, earth science, natural resource economics

JEL Classification Numbers: O32, O38, Q28

Contents

The Value of Information: A Background Paper on Measuring the Contribution of Space-Derived Earth Science Data to National Resource Management

Molly K. Macauley*

I. Introduction

> "We find the value of information is not zero, but it is not enormous, either."
> *—William D. Nordhaus, Sterling Professor of Economics, Yale University, writing about the value of weather and climate information, 1986*

> "If we'd been able to produce a forecast last spring that California would be deluged this winter, it would have been worth whatever research investment was involved, if only because of the human misery it would have relieved."
> *—D. James Baker, then Administrator of the National Oceanic and Atmospheric Administration, writing shortly after heavy rains had flooded many parts of California, 1995*

The mystery of the "value" of information… So often studies of information find its economic benefit—its value—to be smaller than conventional belief might suggest. The explanation lies in the characteristics of information and how decisionmakers use it.

This study, prepared at the request of the Office of Earth Science at the U.S. National Aeronautics and Space Administration (NASA), describes a general framework for conceptualizing the value of information and illustrates how the framework might be used to value information from earth science data. The framework serves two purposes. One purpose is provision of a common basis by which to conduct and evaluate studies of the value of earth science information that serves a variety of uses, from improving environmental quality to protecting public health and safety. The second purpose is to better inform decisionmakers about the value of data and information. Decisionmakers comprise three communities: consumers and

* Molly K. Macauley is a senior fellow at Resources for the Future. E-mail: macauley@rff.org. The support of the Office of Earth Science, National Aeronautics and Space Administration, and Resources for the Future is deeply appreciated. Responsibility for errors and opinions rests exclusively with the author. This paper is an updated and revised version of a draft report originally prepared in September 2002.

producers of information, public officials whose job is to fund productive investment in data acquisition and information development (including sensors and other hardware, algorithm design and software tools, and a trained labor force), and the public at large.

The next section of this paper describes the value of information (VOI) framework and previous studies based on it. The paper then assesses directions for next steps in better understanding VOI obtainable from applications of earth science data to real-world resource management. In this section, the paper uses examples from the focus in NASA's earth science office on national initiatives undertaken jointly with other federal agencies. Through these initiatives, which address such public services as aviation safety, carbon management, and homeland defense, the office is seeking to provide earth science data and information to other federal agencies to better enable them to carry out their public responsibilities.

A note about "earth science" is also in order for readers who may be unfamiliar with NASA's work in this area. The discipline involves the earth and earth's processes—air, water, land, habitat, and their interaction. NASA collects earth science data from space and, to a lesser but important extent, from aircraft. Usually the data are most useful when combined with some amount of "ground truth" data, or data collected *in situ*. Earth science has been part of NASA's activities since the 1960s. NASA has pioneered the design, development, and testing of the sensors, spacecraft, other hardware, and software to collect earth science data and has also contributed to the study and application of these data to improve our understanding of the earth and our management of its resources.

II. Overview: The "Value" of Information

This section offers a generic description of the value or benefit of information and summarizes many of the numerous studies that have assessed VOI in a host of applied areas. After this conceptual discussion, the paper turns to the application of VOI to earth science data.

VOI is essentially an outcome of choice in uncertain situations.[1] Individuals may be willing to pay for information depending on how uncertain they are, and on what is at stake. They may be willing to pay for additional information, or improved information, as long as the

[1] Hirshleifer and Riley (1979) and McCall (1982) offer the classic overviews of general approaches to understanding the value of information.

expected gain exceeds the cost of the information—inclusive of the distilling and processing of the information to render it useful.

More specifically, the general conclusions from models of information are that its value largely depends on several factors:

1. how uncertain decisionmakers are;
2. what is at stake as an outcome of their decisions;
3. how much it will cost to use the information to make decisions; and
4. what is the price of the next-best substitute for the information.

From (1), VOI depends on the mean and spread of uncertainty surrounding the decision in question. For example, Evans et al. (1988) model the value of monitoring information for radon in homes and point out that the value depends partly on the range of remedial actions available to the household. In particular, if few actions are available, then information can have little value even if it virtually eliminates uncertainty. By contrast, if the costs of actions widely diverge, then information about radon levels may be quite valuable even if it reduces uncertainty very little. The authors also illustrate that VOI can be measured based on a given quality of information, or it can be measured based on how its value changes with changes in different attributes of information—for instance, greater frequency of collection or improved accuracy.

From (2), the value depends on the value of output in the market—that is, the aggregate value of the resources or activities that are managed, monitored, or regulated. In other words, a willingness to pay for data about oil exploration potential is in part a function of the price of gas. More formally, willingness to pay for information is *derived* demand—demand emanating from value of the services, products, or other results that in part determine this worth. In cases where VOI pertains to nonmarket goods and services, output measures are also used. For instance, in the case of human health or safety, the "output" measure is typically expressed in terms of the value of a statistical life (a measure routinely used by government safety and health regulators). In cases where the information pertains to the environment, the "output" is often expressed in terms of measures of the value of environmental quality or the value of avoided damages due to actions that may be taken in light of the information.

From (3) and (4), it is important to note that usually there are substitutes for information (traditional "windshield" surveys and aerial photography are used instead of satellite data for monitoring some types of land use, for instance). In addition, processing and interpreting data to make them usable can often be a major roadblock to realizing the value of data and information

—for example, a recent National Research Council study emphasizes that most state and local decisionmakers lack financial, workforce, and technical (hardware and software) resources to use remote sensing data or apply tools for its interpretation and use (see National Research Council 2001), even though the data could prove very useful for certain types of decisions.

Generally, the larger are (1) and (2), the larger is VOI. The larger are (3) and (4), the smaller is the value. These values are also dependent on the individual who is using the information. A decisionmaker usually has subjective probabilities about the quality of the information and will make use of additional information to "update" his prior beliefs. This influence on VOI is the widely accepted applicability of Bayesian probabilities to characterize how individuals perform this updating.

IIA. The Usual Framework

The mathematical formulation that underlies these general characteristics of information is a stated-preference approach. Individuals are assumed to form subjective opinions about the probabilities of two states of the world—say, the simple case of "rain" and "no rain." The value of information is in permitting the person to revise estimates of these probabilities. In the cases of some of the applications currently under way in NASA's earth sciences activities, the counterparts to "rain" and "no rain" might be described along these lines (based on discussion of the applications in National Aeronautics and Space Administration 2002):

> *Energy forecasting:* the presence of solar thermal or geothermal resources compared with their absence. In this application, a possible contribution of earth science to decision support is an improved toolkit with which to assess the likelihood of quantities of these resources and more accurately map their spatial distribution for the purpose of applying this understanding to use and manage global energy resources.
>
> *Carbon management:* improved modeling and measurement of the carbon cycle compared with current understanding of the cycle. Here, earth science may provide improvements that are sufficiently adequate to enable policymakers to implement an effective carbon management regime (e.g., carbon control or carbon trading).
>
> *Aviation safety:* improvements in weather forecasting. Earth science may enable increased efficiency and safety of air travel.

Formally, the typical model follows this specification:

Maximize expected value: $E(y \mid A) = p y_{A1} + (1- p) y_{A2}$

Subject to a budget constraint: $y = P_X X + P_I I$

In the first equation, y is income, A is the state of the world (say, A_1 is crop yield if it rains; A_2 is yield if it doesn't rain), and *p* is the probability of rain. The second equation represents the limits, or budget constraint, facing the individual in spending resources to purchase, process, and use information I at price P_I and to purchase and use all other goods and services X at price P_X.

The result after deriving the first-order conditions from the maximization is that the person should buy additional information until the expected marginal gain from another piece of information is equal to its cost. Usually, expected value is represented by a utility function, about which different assumptions can be made as to its functional form, which in turn can proxy the individual's attitude toward risk (she can be a risk lover, or be risk averse, or be risk neutral).

One of the best textbook examples of how this model operates is reproduced in Table 1 and Figure 1 (This example is from Quirk 1976; see also additional discussion in Macauley 1997). Suppose a farmer can harvest his entire crop today at a cost of $10,000 or half today, half tomorrow at a cost of $2,500 per day. The harvested crop is worth $50,000. Table 1 indicates the "payoff" to the farmer in the event of heavy rain. In expected-value terms, these payoffs are $40,000 to decision A and *p* ($22,500) + (1 – *p*) ($45,000) to decision B. If *p* = 5/22.5, then the decisions give the same payoff if the farmer is "risk neutral." If he were risk averse, he would want a lower value of *p* before he would wait to harvest.

Table 1. The payoff matrix (from Quirk 1976, 309)

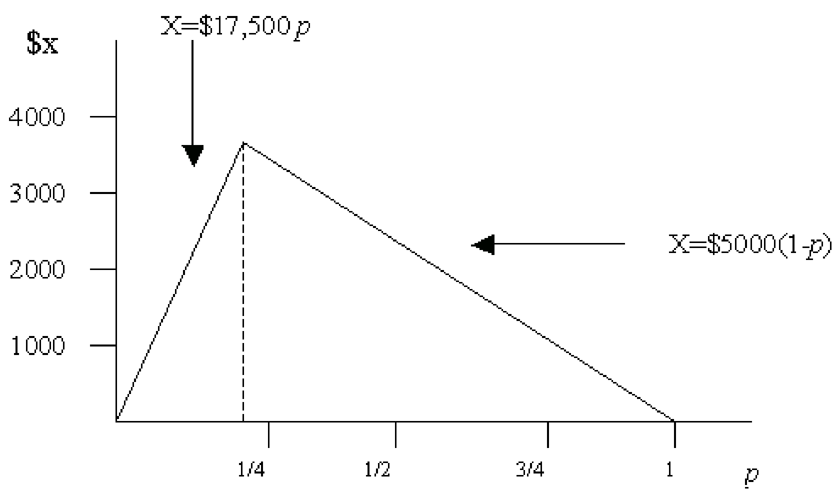
Nature: / *Decision:*	*Heavy rain tomorrow*	*No heavy rain tomorrow*
A. Harvest all today	$40,000	$40,000
B. Harvest over two days	$22,500	$45,000

If it is possible to forecast the weather, then *p* is the probability that the information the farmer receives is that there will be a heavy rain tomorrow with certainty (and (1—*p*) is no rain, with certainty). Since it is a subjective probability, *p* can vary among different farmers. The expected payoff with information is then

$$p\ (\$40{,}000) + (1—p)\ (\$45{,}000)$$

If \$x is the most the farmer would pay for information, then \$x is equal to the difference between the expected payoff with information, and the expected payoff without information. VOI varies with *p* as in Figure 1.

Figure 1. Value of Information (based on Quirk, 1976)



The value is maximized at p = 5/22.5 (where \$x = \$3,888); as above, this is the *p* at which the farmer flips a coin. Information can thus make the biggest difference here. The value of information is zero at $p = 0$ and $p = 1$, since at these extremes, the farmer is already certain in his own mind whether it is going to rain, and information is extraneous (even if the farmer is wrong).

Applications of the model can show the effects of changing the amount or quality of information as well as subsequent revisions that the individual may make of the probability (the Bayesian updating referred to earlier).

Revisiting the overview, then, the implications for VOI from this approach are as follows:

Information is without value

- when individual's subjective beliefs are at extremes (p = 0 or p = 1);
- when there are no costs associated with making the wrong decision;
- when there are no actions that can be taken in light of the information.

Information has less value

- when individual's subjective beliefs are close to extremes;
- when the costs of making the wrong decision are low;
- when actions to take are very limited.

Information has the most value

- the more indifferent is the decisionmaker among her alternatives (flips a coin);
- the larger are the costs of making the wrong decision;
- the more responsive are the actions that can be taken.

Those implications explain the plight of many populations in developing countries: even if severe-weather forecasts were more accurate, in many cases, there are few actions that can be taken in light of the information. They also account for the well-documented incentive for people to build homes along floodplains: even if these are better mapped, the costs of making the wrong decision can be low, mitigated by federal flood insurance.

It is important to note that information can not only influence probability but also inform the decisionmaker by affecting his expected value of the harvest based on information about crop quality and other conditions unrelated to the probability of rain. In formal terms, this means that the expressions y_{A1} and y_{A2} are both functions of I, just as the probability p is a function of I. In other words, additional information can have two effects: it permits the decisionmaker to revise his choice or to revise the probability attached to the two states, or both. For example, the choice whether to harvest may be influenced by information about crop health, irrespective of the probability of rain. A slightly more complex specification of the mathematical model that makes these relationships explicit is in Nicholson (1989).

From this discussion, ultimately a decisionmaker must process a host of information into a decision that reflects assessment of the probabilities of various states of the world. To the extent that information alters *a priori* probabilities (the likelihood of rain) or improves understanding of the choices themselves (the quality of the harvest) and allows individuals to make better decisions, it is a resource that has economic value.

In applying the model to NASA's contribution to decision support tools for federal agencies, agencies may or may not be able to express their budget constraint for decision support services (DSS) formally, but most will certainly be able to describe the resources they save, the productivity they gain, or the reallocation of resources from other activities (the "X") to the space-derived information (the "I"). All of these are suitable approximations for the values reflected in the model.

IIB. Previous Studies

Studies of the value of information have a long and far-ranging history that brings a wealth of examples on which to build approaches for earth science applications. The studies fall into three types of models: econometric estimation of output or productivity gains due to information; hedonic price studies; and contingent valuation surveys. Each of these models sheds some light on approaches that might be taken by NASA, although none of the models are a "perfect fit" for several reasons discussed later in this section and pertaining largely to the data-intensive requirements of the models.

IIB1. VOI Measured by Gains in Output or Productivity

Most of the early VOI studies treated the value of weather information for agriculture production and management. Johnson and Holt (1986) note 20 such studies dating from the 1960s on, including applications to bud damage and loss; haymaking; irrigation frequency; production of peas, grain, soybeans, and grapes (raisins); fed beef; wool; and fruit. More recently, Adams and coauthors (1995) observe changes in crop yields associated with phases of the El Niño–southern oscillation (ENSO) and use the market value of the yield differences to estimate the commercial value of the ENSO phenomenon. Other studies include Lave 1963; Sonka and coauthors 1987; Babcock 1990; Pielke 1995; Nordhaus and Popp 1997; and Hersh and Wernstedt 2001. Some studies use a times series of the behavior of commodity prices in futures markets to infer weather-related values. Two examples are Roll (1984), who studies orange juice futures, and Bradford and Kelejian (1978), who study stock prices of wheat. Changes in futures and stock prices following weather predictions over time are taken as measures of the value of the forecast.

Additional studies have encompassed a wide variety of other topics, ranging from the effects of weather forecasts on the decision to use tarps in the trucking industry (Nelson and Winter 1964) to the value of information in the form of labeling on consumer products (for example, see Evans et al. 1988), the effects of information about differences in gas prices on gasoline demand in urban areas (Marvel 1976),[2] and the problem of risk assessment by insurers (a classic discussion of this extensive literature is in Pauly 1968). Other recent studies focus on the value of space-derived data for natural disasters (Pielke 1996; Williamson and coauthors 2002), geomagnetic storm forecasts (Teisberg and Weiher 2000), geologic maps (Bernknopf et al. 1997) and deforestation in the Brazilian Amazon (Pfaff 1999). The latest detailed applications of VOI are to studies of the information role played by the Internet; for example, how consumers' ability to obtain information through the Internet and shop online influences prices charged for goods and services (Kauffman and Wood 2000).

The approaches of the studies range from highly sophisticated econometric studies and detailed simulation models to less detailed, "back-of-the-envelope" estimates. Given abundant information—for example, the large amounts of data on crop yields, rainfall, and crop prices in the case of agriculture production—researchers can undertake rich statistical analyses. The typical study of the value of weather information for agriculture compares expected farm profits under average but uncertain weather patterns with profits that might be expected if rain could be accurately forecast. In other topic areas, too few data may be available and the studies tend to be anecdotal.

All of the studies start from the basis of the contribution of information to the value of output, as pointed out above. Many of the socioeconomic benefits described in the current earth science applications program are based on a similar approach: they multiply the total value of output, at-risk assets, and other aggregate activity by an estimated percentage by which the activity may be affected by NASA's earth science "information outputs." For instance, the public health project is using the total annual costs of asthma to the United States (in direct medical expenditures and lost productivity) as a benchmark for contributions of earth science outputs to health and the environment. The community preparedness for disaster management project is using the total value of loss to life and property associated with natural disasters as a benchmark.

[2] The examples of labeling of consumer products and differences in gas prices are among a large literature on "advertising as information" that uses the same conceptual framework as studies of the value of weather and other information. See, for instance, discussion in Nelson (1974).

Because NASA has indeed begun to consider this approach, it is interesting to summarize the results in the literature. In a review of these studies, Nordhaus (1986, p. 3) notes,

> All of the studies I know of the value of perfect information find its value to be on the order of one percent of the value of output. For example…one study found that if you halve the standard error of precipitation and temperature, say from one percent to one-half percent, or one degree to one-half a degree, you get an improvement in the value of the output on the order of 2 percent of the value of wheat production. A study of cotton gave the same order of magnitude. I have looked at a number of studies in the area of nuclear power and energy, trying to determine the value of knowing whether nuclear power is ever going to pan out. Again, perfect information is worth on the order of one percent of the value of the output.

Roll (1984) reaches similar conclusions in his study of the effect of weather information on the behavior of futures markets for orange juice and the effect of weather information on these markets, finding that "there is a puzzle in the orange juice futures market. Even though weather is the most obvious and significant influence on the orange crop, weather surprises explain only a small fraction of the observed variability in futures prices."

If conclusions such as those are borne out, then compared with the value of the final product, whether measured as the value of production or capitalized into futures prices, the incremental gain from information appears to be small. To be sure, in industries where the value of output is in the billions of dollars, a small percentage of a large number is a large number for the value of information.

But many observers wonder why the values are not larger. This observation is illustrated in an editorial by a former administrator of the National Oceanic and Atmospheric Administration, quoted in the introduction (see Baker 1995). His conclusion might be easier after the fact ("If only I had known"). It is much more difficult to arrive at such a conclusion before the fact, however. Some of the reasons why pertain to the four characteristics of information in Section IIA: using information can be costly, and there are often good substitutes for different kinds of information at lower cost. In general, it is only *ex ante*—before the event—that we are willing to pay for information, because afterward it is less important. Indeed, the *ex ante*, or expected value, is what experts agree determines the value of information, as in the model described earlier. If the probability of an event is either very unlikely or very likely, or if the actions that can be taken to avert its effects are minimal, then this value can be quite low.

In addition, VOI can be reduced after second- and third-order effects, or repercussions, formally known as the dynamic responses. For instance, in the case of agricultural production, increased output brought about by better weather information can cause crop prices to fall, thereby resulting in a decline in the value of output and a decline in the value of information for the industry (although of course, consumers would benefit from the lower prices). Speculating—merely speculating—in the case of earth science applications, we might expect, for example, that some tools intended to improve aviation safety by reducing departure and arrival delays (the Terminal Convective Weather Forecast) could result in increased air traffic and in turn, the possibility of additional accidents.

IIB2. Hedonic Pricing Studies

Another large literature that may be useful in earth science applications dates from the 1970s and uses wage and housing prices to infer the value of weather information, under the hypothesis that it is capitalized into the prices of such goods and services. These studies are premised on hedonic price theory, by which researchers model the equilibrium market for a commodity and then derive and estimate a function relating price to characteristics of the commodity. Coefficients on the characteristics are then interpreted as dollar estimates of the implicit value of the characteristics.

Rosen's (1976) study is among the seminal theoretical and empirical research that considers the extent to which interurban wage differentials reflect differences in urban quality of life. He econometrically explains differences in the average wages for various occupations in a cross section of cities. He uses as explanatory variables not only personal characteristics influencing wages, such as education and age, but also measures of urban amenities and disamenities. These "quality of life" factors include pollution (water pollution, particulates, sulfur dioxide, inversion events), the crime rate, crowding (population density, population size, central city density), market conditions (unemployment rate, population growth), and climate (number of rainy and sunny days, number of extremely hot days). He expects higher wages in cities with disamenities compared with nicer cities, and this compensating differential is expected to work in the opposite direction for urban amenities: a city with pleasant weather, for example, may not have to offer higher-than-average wages to attract workers and may even be able to offer lower wages. Rosen finds that climate variables are statistically significant in the expected directions. Wage rates are higher, for instance, in cities with rainy or extremely hot weather.

In a study of housing prices, Blomquist and coauthors (1988) estimate interurban quality-of-life indices using households' monthly housing expenditures (rent for tenants, imputed rent for homeowners) and measures of climate, environmental quality, crime, and other variables.

The climate measures include precipitation, humidity, heating degree-days, cooling degree-days, wind speed, and sunshine. All of the climate variables are found to be statistically significant determinants of housing expenditure, with an inverse correlation between expenditure and precipitation, humidity, and heating and cooling degree-days and a positive correlation between expenditure, wind, and sunshine.

Blomquist and coauthors also include wages in their study and combine the housing expenditure and wage data in a model that estimates the "full implicit price" of urban area quality-of-life variables. They find negative prices (that is, a marginal net disamenity) for precipitation, humidity, heating and cooling degree-days, and wind speed.

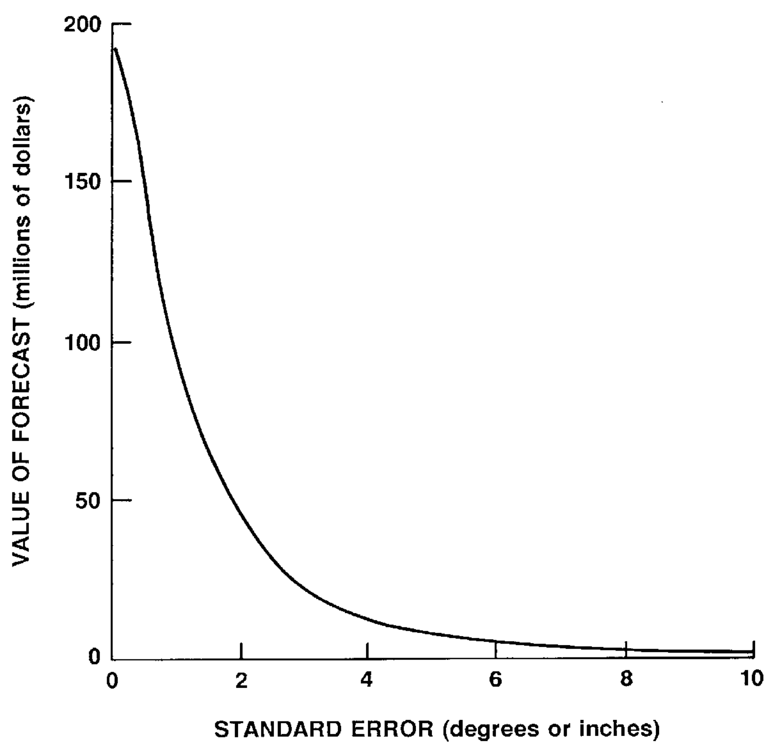
Hedonic approaches to valuing amenities are not without problems of data availability, modeling assumptions, and econometric issues. Freeman (1993) surveys and critiques the methodology of most of the studies to date linking wages and housing prices with environmental amenities. Nonetheless, extending the approaches to include not only average temperatures but also, say, weather variability could enable the models to more closely proxy the value of information associated with weather forecasting. In addition, the hedonic methods could be used to ascertain different values associated with different attributes of a forecast, such as timeliness, frequency, and accuracy. These, in turn, could help inform planners about what types and capabilities of new instruments are most valued by the communities that make use of the data and information. To illustrate, Ausubel (1986) shows the significant variation associated with the value of a weather forecast given its standard deviation (see Figure 2). In similar spirit, Nelson and Winter (1964) use an expected value approach to show which attributes of a forecast matter most to the trucking industry.

IIB3. Survey Approaches: Contingent Valuation

Rather than draw data from real-world observations of real-world choices, another approach uses decisionmakers' responses to hypothetical questions. For example, people can be asked how much they are willing to pay for a specific change in environmental quality. The responses, if honest, are expressions of the value that respondents associate with the change. This approach is sometimes referred to as the survey or interview method, but it is known most typically as contingent valuation (CV). The survey tries to measure the valuation of respondents based on, or contingent on, their willingness to pay —"putting their money where their mouth is."

CV methods have a long history, beginning in the 1960s with questionnaires used to estimate the benefits of outdoor recreation in Maine. Mitchell and Carson (1989) relate much of the early history and offer an excellent overview of the literature and approach. Cummings and coauthors (1986) and, more recently, Freeman (1993) are also excellent references. Other applications of CV have included assessing the value of visibility at the Grand Canyon; national water quality; information about natural hazards (earthquakes); and hunting, fishing, and other recreational permits. CV studies were conducted by parties to the litigation over penalties for damage to land, water, habitat, and other resources as a result of the *Exxon Valdez* oil spill. The method was also the focus of an advisory panel convened by the National Oceanic and Atmospheric Administration to consider the general problem of how best to assess natural resource damages.

Figure 2. The value of information and its characteristics (Ausubel, 1986)



How best to design surveys to elicit honest expressions of valuation has been the subject of considerable research and testing, and where possible, the results of CV studies have been compared with results from direct valuation studies, such as those described above. The jury is still out on the acceptability of the approach, although its proponents correctly note that in many cases, there is no alternative means of eliciting values about some types of public goods, including natural resources and other environmental amenities. In addition, design and administration of a high-quality CV survey can be expensive.

Subject, then, to the advantages and disadvantages of CV studies (and of course, the more direct valuation methods have their own limitations), it may be appropriate for some NASA earth science applications areas to use CV-type surveys to elicit from federal agencies the value of space-derived earth science to their decision support systems. In addition, different attributes of earth science information—timeliness, accuracy, and frequency—could be the subject of a small-scale CV survey of federal partners.

III. Further Applications to Space-Derived Earth Science

This section further links some aspects of the conceptual approaches to VOI with the NASA earth science applications strategy. The examples offered here are highly simplified and stylized. They are meant to illustrate approaches for future in-depth study, review, and application. The purpose of the VOI studies would be to better understand, explain, and where possible assess the cost-effectiveness of assimilation and operational use of earth science data and science results.

At present, NASA is linking applications themes to decision support services for "service providing" federal agencies—those that supply or ensure services for the public. From Section I above, this means that demand for applications tools is derived demand—that is, demand derived from government requirements to fulfill statutory responsibilities. A critical challenge in this case is separating progress toward objectives from the impact of external factors, since the objectives of federal programs are the result of complex political decisions outside the program's control. It may also be the case that a tool designed for a specific DSS may be orphaned if the DSS is canceled. In a narrow sense, then, the usefulness of earth science applications is thus critically dependent on law, policy, and regulation of public health and safety and the environment. In a broader sense, though, it is important to note that earth science applications could well be picked up by industry or state or local decisionmakers, thus making a contribution despite federal programmatic shifts or cancellations.

IIIA. Special Notes

Two notes are in order about VOI studies and federal agency use of space-derived earth science. First, whereas most studies reviewed in Section II describe the benefits and costs of using information, cost-effectiveness rather than cost-benefit analysis is the appropriate context for VOI study, given the earth science applications' focus on federal agencies. Cost-effectiveness takes into explicit account that the agencies are mandated to perform certain functions to which the DSS and, in turn, the earth science contribution to DSS are applied. For example, some of the agencies involved in earth science initiatives are required to enforce environmental regulations, provide aviation safety, and protect public health. In all cases, the agencies must carry out the mandates subject to budget constraints. The agencies are thus restricted in two dimensions: the mandate and the budget constraint—and the appropriate determination of the value of the contribution involves one of these two questions:

- Does the contribution enable the agency to carry out the mandate and save money within the budget constraint? That is, for instance, can it save more lives within a fixed budget?
- Or does the contribution enable the agency to save a given number of lives at a lower cost? That is, can it achieve the same benefit (number of lives saved) but at lower cost?

Cost-benefit methodology does not allow for the statutory and budgetary constraints but asks only, how many lives can be saved and at what cost?[3] This open-ended question is usually inappropriate for study of federal programs.

The second (and related) note in understanding VOI in application to federal programs is that these programs produce public goods, such as public health and safety, environmental improvement and protection, and the maintenance of viable U.S. agricultural performance in world markets. Valuing the output of public goods is more difficult than valuing information based on its contribution to the value of output in industry, for which market values are readily available. The studies reviewed in Section II address market outputs, not public goods. For this

[3] An additional measure is whether there is follow-on investment in research and development or commercial adoption by the private sector, but these measures go beyond the current objectives of NASA in focusing on serving sister agency requirements for delivering public services.

reason, some adjustments to the approaches to estimate VOI are necessary in its application to the government sector of the economy.

IIIB. Assessing the Value of Information

Assessment can take place at several stages in the development and ultimate use of earth science contributions. For internal program management and reporting to the U.S. Office of Management and Budget (OMB), for example, "due diligence" is required: did NASA meet the milestones in its strategic plan? Among agency partners, the relevant question is whether space-derived earth science enhanced ability and capability to better enable the partners to deliver their statutorily required services. And with respect to the public, the most relevant question is what is the value of information. This ultimate measure transcends NASA and agency partners but reflects the actual import of the program, and in fact, realizing the socioeconomic benefits that are represented by these impacts are the given the highest priority in NASA's earth science strategic planning (at http://www.earth.nasa.gov/visions, p. 5). If the VOI approach can assist at this level, VOI can also be a useful means of communicating results (note, however, that OMB performance reporting does not at present require impact evaluations).[4] An additional opportunity not addressed here is the feedback loop of how the identification and enforcement of reaching milestones feeds back into revision of the strategic plan—the complementary role for program evaluation in requiring agencies to describe performance and use it in program planning, modification, implementation, and innovation.

The examples below offer approaches to the following types of measures and the appropriate audiences for each measure:

1. *Output measures.* These measures can serve as performance measures for program management largely within the earth sciences office, NASA, and OMB. The measures support the assessment of "outputs" defined in the Earth Science Strategy for 2002–2012. There, an earth science output is a product or service that may take the form of algorithms, models, data, validated and verified data, and/or science results, standards, prototypes, or guidelines.
2. *Productivity and enabling measures.* These measures are particularly relevant to the earth science office, NASA, Congress, and the public at large. The measures answer

[4] See U.S. General Accounting Office (1997), now U.S. General Accountability Office.

the cost-effectiveness question posed to the agencies whose DSS make use of space-derived earth science: "in fulfilling your governmental responsibilities and objectives, what increase in productivity, or in some cases, what new approaches, did NASA earth science contributions permit?"

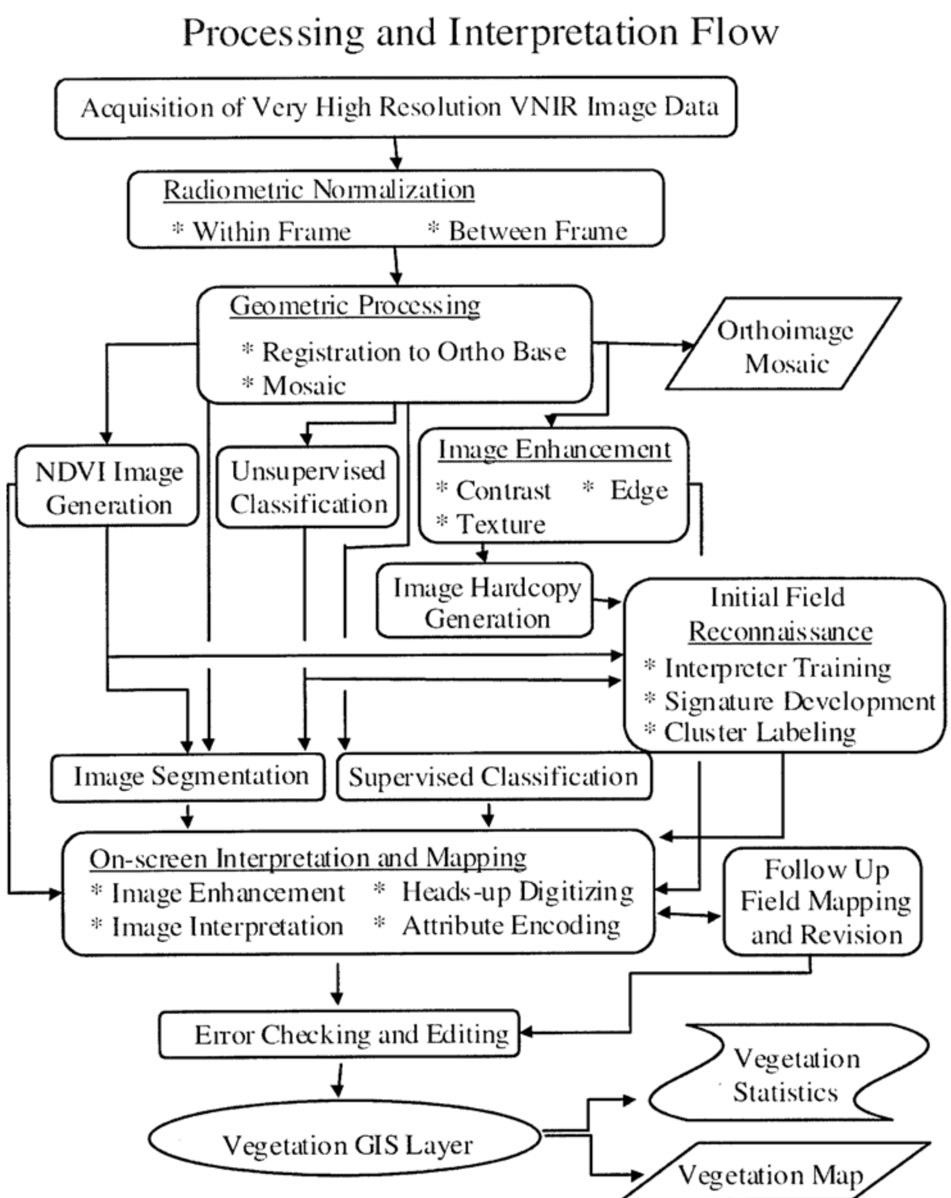
3. *Societal benefits.* Measures of these benefits are relevant to the same audiences as productivity and enabling measures. In the earth science strategy for 2002–2012, the benefits are referred to as socioeconomic benefits and are defined as the impact of the contribution in benefiting society at large through support of agency DSS activities. These measures come closest to the VOI studies described in previous sections of this paper because their purpose is to assess the overall contribution of information to improving quality of life.

IIIB1. Output Measures in Space-Derived Earth Science

Figure 3 illustrates a "transformation" process of earth science inputs into outputs. This example, from a project in NASA's Earth Observations Commercialization Application Program, involved algorithm development for vegetation indices. Using this illustration as a template, some or all of the wires and nodes in such a "wiring diagram" could be called the output of earth sciences effort. The value of the effort, then, is the extent to which the wires and nodes are defined, constructed, and made operational to produce an output on time and within budget. The 1993 Government Performance and Results Act essentially asks for performance definitions much like what is captured in this sample diagram and then asks for the measurement of progress in completing it. In current NASA planning, the diagram takes the form of "roadmaps." Wiring diagrams and roadmaps are both organizational devices to explain long-term strategic goals, annual performance goals, and progress toward these goals in earth science applications. Note that the diagram does not directly address VOI of the outputs, but it does show necessary steps en route to outputs whose VOI will be demonstrated in applying the outputs to actual decisionmaking.

Figure 3. Output Measures: "Wiring Diagram"

Source: San Diego State University, Ogden Corporation, and the Stennis Space Center of the National Aeronautics and Space Administration.



IIIB2. Productivity and Enabling Measures

Figure 4 outlines a set of questions that might be asked of federal agencies to document the value of earth science outputs or information to the agencies as they implement mandates. The questions essentially ask what difference the earth science contribution has made in improving the ability of the agency to carry out its tasks more productively or achieve its goals. As noted above, the agencies operate subject to mandates and budget constraints, so the objective of cost-effectiveness defines this output measure. The key to credible responses from agencies is the criterion underlying contingent valuation (CV) in Section II above. The aim is to ascertain what agencies would be willing to pay to use the outputs: What do the outputs save or enable, what would an agency do *without* the outputs, and how much more would it cost or how much less effective would the results be? That is, rather than saying, “The earth science contribution is terrific,” the agency’s response should be, “Because of the earth science contribution, we have saved *x* amount of money and improved implementation of our mission by *y*.” The wiring diagrams or roadmaps in Figure 3 could play a role here if they were designed to model the agency DSS. The earth science contribution could be mapped to the diagram to define and then measure the effect on agencies’ outcomes.

Figure 4. Enabling and Improving Human Health and Environmental Protection: A *Hypothetical* Earth Science Application for Monitoring Invasive Species

Note: All entries are fictional.

Benchmark: Cost factors		*Benchmark: Allocation of costs*	*Earth science contribution to cost reduction*	*Enabled cost reduction $ millions/ year*
Data collection *In situ $20 million/year*				
	Access	80%	↓ 5% to 8%	$0.8–1.28
	Routine measurement	5%		
	Frequency of measurement	5%	↓ 20% to 25%	$0.2–0.25
	Quality	10%		
Remote *$10 million/year*				
Validation and verification *$.05 million/year*				
Data analysis *$15 million/ year*				
	Interpretation	80%		
	Forecast, prediction	15%	↓ 3% to 8%	$.07–0.2
	Quality control	5%		

IIIB3. Societal Benefits

Figure 5 suggests some ambitious steps to take to identify and measure the most difficult but most salient performance measure, "socioeconomic benefit" or "impacts" (to use terms from the NASA earth science strategic plan). These steps follow the VOI model in Section II. They would require information about the percentage improvement brought about by the earth science contribution and some baseline measure of the value of the agency DSS in attaining the benefits of the agency's mandate.

Examples in the figure show valuation approaches for aviation safety in terms of (a) cost savings and (b) value of lives saved—the two sides of cost-effectiveness. The figure also shows ways to think about agricultural productivity gains and air quality improvements.

Some current NASA applications follow this general approach in describing their performance measures. The program managers discuss the value of an agency's activity and use this to indicate the potential impact of earth science. For example, in the case of renewable energy forecasting, NASA notes the potential percentage cost savings in DSS and expected to be enabled by earth science outputs, then multiplies these savings by the forecasted value of the output of the relevant energy industries to project dollar benefits (see NASA Office of Earth Science 2002).

Caution is necessary in assessing societal benefits for at least four reasons. One is that the forecasts assume cost-effective and successful technical assimilation and integration of the contribution into the DSS. A second caution is that a variety of factors influence future savings. In the case of renewable energy, these include innovation in human and physical capital, trends in learning by doing and manufacturing scale-up in renewable energy technology, regulatory trends in the electricity industry (toward deregulation), the significant economic competitiveness of conventional fossil fuels, federal and state energy policy, and environmental regulation. A third, related caveat is that technical, regulatory, and financial uncertainty characterizes the forecasts of the value of the activity. A fourth reason for caution is that these measures of benefits are gross—they do not subtract the costs incurred to obtain them—and should not be confused with overall public net benefits. At a minimum, then, "impact" estimates for this and other applications need contextual statements noting caveats and should include uncertainty ranges ("if our assumptions do not hold, then our expected results may range between these values").

The following categories of possible measures for valuing the contribution to national initiatives are intended to provoke discussion about developing useful and feasible metrics. The discussion is preliminary, however, and fully recognizes that at this time, earth science applications investigations are just now under way.

Figure 5. "Impact" or "Socioeconomic Benefit" Measures Based on Earth Science VOI: A Stylized Description

(1) Agency mandate: save lives, protect environment, improve agricultural competitiveness, etc.

→ (2a) Range of values of agency cost of DSS to implement (1).

(3a) Range of values of savings or productivity gains due to earth science data by way of DSS.

(4a) Rough estimate of VOI (subtract (3a) from (2a) and express as a range, with associated contingencies/uncertainties/caveats described).

OR

→ (2b) Range of size of benefit due to earth science via DSS in implementing (1).

(3b) Rough estimate of VOI (weight (multiply) (2b) by relevant base value).

Examples:

Aviation safety

Cost to produce without earth science data: $x/year (based on budget data).

Cost to produce with earth science data: $y/ year to $z/year (based on detailed assessment of use of earth science data in DSS).

Implied earth science "VOI": $x–z/year to $ x–y/year.

Aviation safety—Another approach

Benefits per year (estimates of lives saved) enabled by earth science data: y to z lives/year.

Implied earth science "VOI": y to z multiplied by federal value of statistical life ($/year).

Agricultural competitiveness

Value of output: $x/year.

Improvement in output due to earth science data via DSS: y to z%/year.

Implied earth science "VOI": product of $x and y to z%/ year.

Carbon control for air quality

Cost of damages due to uncertainty in measurements of emissions: $x/ton/year.

Or cost of remediation that could be avoided if uncertainty were reduced: $y/ton/year.

Both are implied earth science "VOI" in reducing uncertainty through contribution to DSS.

IV. Conclusions

This paper has reviewed models and studies of the value of information and offered preliminary observations about using these approaches to assist NASA in designing and implementing useful measures of performance for its earth science activities.

The state of the art in understanding the value of information reflects general agreement on how to model an individual's decision calculus and some useful implications about the value of information: when it is most and least valuable and its relationship to an individual's subjective prior opinions and ability to take action in light of the information. Most estimates of the value of information suggest that it is not large as a percentage of final output (in agriculture, trucking, and other markets). This result seems inconsistent with some perspectives of the value of information, such as information on natural disasters and loss of life. But in these cases, the *ex ante* and *ex post* values of information need to be distinguished; in some instances, people's prior beliefs about the low probability of hazards figure prominently in reducing the perceived value of the information. Finally, consideration must be given to the costs of actions that could be taken, or not taken, in anticipation of and in response to the information.

References

Adams, Richard M., et al. 1995. Value of Improved Long-Range Weather Information. *Contemporary Economic Policy* 13(3): 10–19.

Ausubel, Jesse. 1986. Some Thoughts on Geophysical Prediction. In *Policy Aspects of Climate Forecasting*, edited by Richard Krasnow. Proceedings, May 4. Washington, DC: Resources for the Future, 97–110.

Babcock, Bruce A. 1990. The Value of Weather Information in Market Equilibrium. *American Journal of Agricultural Economics*, February: 63–72.

Baker, James D. 1995. When the Rains Came. *The Washington Post*. 25 January, A25.

Bernknopf, Richard L., David S. Brookshire, Michael McKee, and David R. Soller. 1997. Estimating the Social Value of Geologic Map Information: A Regulatory Application. *Journal of Environmental Economics and Management* 32: 204–18.

Blomquist, Glenn C., Mark C. Berger, and John P. Hoehn. 1988. New Estimates of Quality of Life in Urban Areas. *American Economic Review* 78(1): 89–107.

Bradford, David F., and H.H. Kelejian. 1977. The Value of Information for Crop Forecasting in a Market System. *Bell Journal of Economics* 9: 123–44.

Cummings, Ronald G., David S. Brookshire, and William D. Schulze, eds. 1986. *Valuing Environmental Goods: An Assessment of the Contingent Valuation Method*. Totowa, NJ: Rowman & Allanheld.

Evans, John S., Neil C. Hawkins, and John D. Graham. 1988. The Value of Monitoring for Radon in the Home: A Decision Analysis. *Journal of the Air Pollution Control Association* 38: 1380–85.

Freeman, A. Myrick, III. 1993. *The Measurement of Environmental and Resource Values*. Washington, DC: Resources for the Future.

Hersh, Robert, and Kris Wernstedt. 2001. Gauging the Vulnerability of Local Water Utilities to Extreme Weather Events. Discussion Paper 01-33. Washington, DC: Resources for the Future, September.

Hirshleifer, J., and John G. Riley. 1979. The Analytics of Uncertainty and Information—An Expository Survey. *Journal of Economic Literature* 17(4), December: 1375–421.

Johnson, Stanley R., and Matthew T. Holt. 1986. The Value of Climate Information. In Richard Krasnow (ed.), *Policy Aspects of Climate Forecasting.* Proceedings, May 4. Washington, DC: Resources for the Future, 53–78.

Kauffman, Robert J., and Charles A. Wood. 2000. Follow the Leader? Strategic Pricing in E-Commerce. Carlson School of Management Discussion Paper (University of Minnesota), 26 November. Available at http://misrc.umn.edu (accessed fall 2002).

Lave, Lester B. 1963. The Value of Better Weather Information to the Raisin Industry. *Econometrica* 31, January/April: 151–64.

Macauley, Molly K. 1997. Some Dimensions of the Value of Weather Information: General Principles and a Taxonomy of Empirical Approaches. In Roger A. Pielke, Jr. (ed.), *The Social and Economic Impacts of Weather*. Boulder, CO: National Center for Atmospheric Research.

Marvel, H. 1976. The Economics of Information and Retail Gasoline Price Behavior. *Journal of Political Economy* 84, October: 1033–59.

McCall, John J., ed. 1982. *The Economics of Information and Uncertainty*. Chicago: University of Chicago Press.

Mitchell, Robert Cameron, and Richard T. Carson. 1989. *Using Surveys to Value Public Goods: The Contingent Valuation Method*. Washington, DC: Resources for the Future.

National Aeronautics and Space Administration (NASA), Office of Earth Science. 2002. National Applications Program: Program Strategy Status, June.

NASA website. http://www.earth.nasa.gov/visions (NASA's Office of Earth Science Strategic Plan and Applications Strategy for 2002-2012).

———. http://ifmp.nasa.gov/codeb/budget2003 (Earth Science FY2003 Performance Plan).

National Research Council, Space Studies Board and Ocean Studies Board. 2001. *Transforming Remote Sensing Data into Information and Applications.* Washington, DC: National Academy Press.

Nelson, Phillip. 1974. Advertising as Information. *Journal of Political Economy* 82(4): July, 729–54.

Nelson, Richard R., and Sidney G. Winter. 1964. A Case Study in the Economics of Information and Coordination: The Weather Forecasting System. *Quarterly Journal of Economics* 78(3): 420–41.

Nicholson, Walter. 1989. *Microeconomic Theory*. Chicago: Dryden Press.

Nordhaus, William D. 1986. The Value of Information. In Richard Krasnow (ed.), *Policy Aspects of Climate Forecasting*. Proceedings, May 4. Washington, DC: Resources for the Future, 129–34.

Nordhaus, William D., and David Popp. 1997. What Is the Value of Scientific Knowledge? An Application to Global Warming Using the PRICE Model. *Energy Journal* 18(1): 1–46.

Pauly, M. 1968. The Economics of Moral Hazard: Comment. *American Economic Review* 58, June: 531–37.

Pfaff, Alexander S.P. 1999. What Drives Deforestation in the Brazilian Amazon? Evidence from Satellite and Socioeconomic Data. *Journal of Environmental Economics and Management* 37(1): 26–43.

Pielke, Roger A., Jr. 1995. Usable Information for Policy: An Appraisal of the U.S. Global Change Research Program. *Policy Sciences* 28(1): 39–77.

———. 1996. Reframing the U.S. Hurricane Problem. Mimeograph. Boulder, CO: National Center for Atmospheric Research, August 1.

Quirk, James P. 1976. *Intermediate Microeconomics*. New York: Science Research Associates.

Roll, Richard. 1984. Orange Juice and Weather. *American Economic Review* 74(5): 861–80.

Rosen, Sherwin. 1976. “Wage-based Indexes of Urban Quality of Life,” in *Current Issues in Urban Economics*, Peter Mieszkowski and Mahlon Straszheim, eds. Baltimore, MD: Johns Hopkins University Press.

Sonka, Steven T., James W. Mjelde, Peter J. Lam, Steven E. Hollinger, and Bruce L. Dixon. 1987. Valuing Climate Forecast Information. *Journal of Climate and Applied Meteorology* 26(9), September: 1080–91.

Teisberg, Thomas J., and Rodney F. Weiher. 2000. Valuation of Geomagnetic Storm Forecasts: An Estimate of the Net Economic Benefits of a Satellite Warning System. *Journal of Policy Analysis and Management* 19(2): 329–34.

U.S. General Accounting Office. 1997. Managing for Results: Analytic Challenges in Measuring Performance. GAO/HEHS/GGD-97-138, May.

Williamson, Ray A., Henry R. Hertzfeld, Joseph Cordes, and John M. Logsdon. 2002. The Socioeconomic Benefits of Earth Science and Applications Research: Reducing the Risks and Costs of Natural Disasters in the USA. *Space Policy* 18: 57–65.