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Cost Analysis for a Recommended NASA Carbon Cycle Initiative

Janette C. Gervin, Paul C. Caruso, Louis A. DeMaio, Charles R. McClain, G. James Collatz, S. Randy Kawa, Watson W. Gregg, Arlyn Andrews, and James Hansen
NASA Goddard Space Flight Center, Greenbelt, Maryland

Forrest G. Hall and Steven Pawson
University of Maryland, Baltimore County, Maryland

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

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ABSTRACT

This volume presents the costs estimated for the science and engineering implementation of the Recommended NASA Carbon Cycle Research, as of August 31, 2001. The research activities have since been refined and folded into a broader program plan for contributing to the President's Climate Change Research Initiative. A brief introduction describes the process used to develop the measurements, activities, and missions from science goals in preparation for costing. Program content is described in much greater detail in a NASA Technical Memorandum entitled Science and Observation Recommendations for Future NASA Carbon Cycle Research.

The costs for science implementation are presented in Section 2 by discipline (atmosphere, land, and ocean), by categories of work within each discipline (e.g., field campaigns, modeling and analysis, etc.), and by year. Section 3 on engineering implementation presents costs for the development of spaceborne missions, aircraft instruments, and supporting technologies, based on the highest priority measurements identified through the workshop process and recorded in the science implementation section. The characteristics and costs of the spaceborne missions were further refined in studies by the GSFC Instrument Synthesis Analysis Laboratory (ISAL), Integrated Mission Design Center (IMDC), Rapid Spacecraft Development Office (RSDO), and Resource Analysis Office (RAO) and by inputs from other NASA Centers. A philosophy of total life cycle costing was followed in all cost estimates. The aircraft instrument costs are based on discussions with prospective instrument developers and include only the cost of the instrument itself. The cost of deployment and data collection is covered in the science implementation budget. The technology development needed to support these activities, including that specific to each measurement/mission and that common to multiple measurements, is then discussed. Costs for a baseline mission set and several scenarios for reduced mission set options are presented. Profiles are also included that spread these mission costs by year. In addition, the costs per year for the total science and engineering implementation effort are summarized.

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1.0 INTRODUCTION

A comprehensive carbon cycle program has been developed that is responsive to the goals and objectives of a broad science community and established working groups. The proposed program intends to make new regional and global measurements and develop integrated models that significantly reduce the uncertainties associated with existing carbon budget estimates. These focussed observations and analyses of atmospheric, ocean, and land carbon cycle processes and their dynamics will provide a quantum step toward better understanding and management of critical carbon sources and sinks.

This volume presents cost estimates for all of the science and engineering elements of the Recommended NASA Carbon Cycle Research, performed under the working titles of the NASA Carbon Cycle Initiative (NCCI) and the Global Carbon Cycle Plan (GCCP), and complements the more detailed plan description provided in the NASA Technical Memorandum entitled Science and Observation Recommendations for Future NASA Carbon Cycle Research. During the planning effort, the terms "initiative" and "program" were often used and reflect the cross-cutting nature of carbon research which involve terrestrial, atmospheric and oceanic science and do not imply that the recommendations necessarily require funding that is over and above what is available in the current Earth Science Enterprise (ESE) budget, although some recommendations may require new funds. The planning exercise simply considered what was needed over the next 10 years to address the primary science questions outlined in the companion Technical Memorandum (TM) and did not address funding considerations.

A workshop process, illustrated in Figure 1, was employed to identify and refine science questions and objectives and to guide related science and engineering activities. The methodology adopted for the resulting instrument and mission studies is shown in Figure 2.

In describing new measurements and their projected costs, it was necessary to consider a number of factors. These included the measurement type, rationale and performance drivers, spatial resolution and extent, geographic location, temporal resolution and duration, timing, special events, repeat cycle, precision, and accuracy. In addition, there were practical considerations, such as data volume, communications requirements, ancillary measurements, prelaunch sensor characterization, algorithms, data processing, post-launch product generation and validation, models, and theory, as well as coordination and linkages with field campaigns, aircraft underflights, and other satellites. Cost estimates were then developed including personnel, travel, hardware development, operations, data collection, and the subsequent data analysis and input to models. Modeling improvements were also considered.

Careful evaluation of all these factors led to a preliminary spaceborne and/or airborne instrument concept, which described the type of sensor that might be able to provide this measurement. In order to develop a reliable approach for planning and costing, instrument characteristics needed to be defined including mechanical (mass, volume, and fields-of-view), electrical, thermal, calibration, contamination sensitivity, pointing, data systems, and onboard processing. More than one concept might work but there could be moderate to severe challenges in making any one or all of these concepts work. Furthermore, the more difficult concepts might provide the best performance. These factors were carefully analyzed to develop the cost of building the representative instruments.

Next, the requirements for the mission as a whole, as required by the measurement, were examined to select the appropriate accommodation (spacecraft and launch vehicle) and to ensure that the measurement provided the information needed. Studies were performed by the ISAL, IMDC, RAO and RSDO to better define the characteristics of missions to measure carbon dioxide (CO_2 Pathfinder and Advanced Atmospheric CO_2), aerosols, biomass (low density/coastal ocean, high density), and ocean properties including particulates. Factors that influence cost include the mission life, mass-to-orbit, system complexity, and technology readiness. A total life cycle cost approach was followed to develop a reliable and comprehensive cost estimate for acquiring each measurement.

2.0 SCIENCE IMPLEMENTATION

In developing the GCCP implementation plan, each of the atmospheric, land, and ocean science discipline groups developed a schedule of activities and budget profiles, which were coordinated and complementary. These activities were meant to support the goals of the President's Climate Initiative and to coincide with and complement the goals and objectives of the Interagency Working Group (IWG), particularly as they related to the North American Carbon Program and other North American and Southern Ocean carbon source/sink experiments. The overall roadmap of science activities and the total proposed science expenditures by year are presented in Figures 3, 4, and 5. Two summary charts showing the budget profile by discipline and by category of activity are shown in Figures 6 and 7. The data are presented by Fiscal Year but costs are given in current year 2001$.

2.1 ATMOSPHERE BUDGET JUSTIFICATION

Total Costs: $138,500K—spanning 2002–2012

For the purpose of developing a budget, the atmospheres component of the NASA Carbon Cycle Initiative was broken down into two major sections: Measurement Activities, and Modeling and Data Analysis. The major activities are presented in Figure 8, Atmospheric Carbon Measurement Activities, and Figure 9, Atmospheric Carbon Modeling and Data Analysis, and the associated costs are shown in Figure 10. Functionally there is continuous interaction between these areas and the budget division between them is not unique. The specific activities considered are explained below. Figure 8, Atmospheric Carbon Measurement Activities, also shows the relevant, major space-based measurement activities, which serve as a backdrop for all of the measurements and modeling discussed here. The costs for the development of aircraft and spaceborne instruments themselves are presented in the Engineering Implementation Section.

2.1.1 Atmospheric Carbon Measurement Activities

Total Costs: $91,200K—spanning 2002–2012

A timeline for Atmospheric Carbon Measurement Activities shown in Figure 8 spans 11 years and includes analysis of data from existing, planned and proposed space missions, participation in field campaigns, algorithm development and calibration, and development and deployment of ground-based and in situ instruments.

The costs associated with near-term aircraft and field campaigns presented in Figure 10 include costs for the investigators, aircraft and instrument usage as well as ground support for both domestic and foreign campaigns. The measurement activity costs are broken into the following categories: Field Campaigns, Algorithm Development and Calibration, and Ground-based and In Situ Instruments.

A. Field Campaigns ($54,900K—2002–2012)

The schedule and budget assume three major field campaigns driven primarily by atmospheric CO_2 issues over 10 years. An initial participation/augmentation in the ongoing LBA is envisioned in the first year. The first major activity is associated with the interagency North American Carbon Program (document in preparation). NASA would provide support for in situ aircraft measurements and flight time in intensive campaign mode as well as continuing support for instrument teams' hardware and data preparation and analysis. The numbers for these activities are based on expenditures for the Stratospheric Aerosol and Gas Experiment (SAGE) III Ozone Loss and Validation Experiment (SOLVE), a multicomponent mission of comparable scope. The second and third major field campaigns would be associated with science-level validation and calibration of expected space-based CO_2 measurement missions. Again, SOLVE serves as the model.

B. Algorithm Development and Calibration ($11,500K—2002–2012)

Algorithm development and calibration are aimed at producing a method to measure CO_2 by remote sensing with unprecedented precision and accuracy. Constituent measurements from AIRS (Atmospheric Infrared

Sounder) and other EOS instruments serve as a test bed to begin developing algorithms for instruments specifically designed for high-precision CO_2 measurements. Algorithm development and calibration of potential sampling biases are fundamentally the key to the ultrahigh precision required for accurately inferring sources and sinks from CO_2 concentration measurements. Several iterations in algorithm development are envisioned, ranging from a basic column method to a more sophisticated method that will fully account for cloud and aerosol sampling interference, to an advanced method producing altitude-resolved data near the surface. Improvements in laboratory spectroscopy for CO_2 and other constituents as well as better calibrated in situ instruments for validation are required. Comparison between aircraft and ground-based in situ and remote CO_2 measurements is a key component as discussed below.

C. Ground Based and In Situ Instruments ($24,800K—2002–2012)

Ground-based and in situ instruments are used for demonstrating remote sensing measurement methods, algorithm development, and calibration/validation. In situ CO_2 from aircraft and, potentially, balloons are needed to link profile and column abundances to the ground-based network data archive. These will also be needed for satellite overpass validation. Ground-based and aircraft-borne remote sensing instruments serve as prototypes for space systems. They will initially be used for proof of concept and will eventually be used to validate and calibrate the satellite data. Both passive and active sensor concepts should be developed. Other in situ instruments that may not have a clear pathway to space, such as CO_2 and O_2 isotopes and eddy flux measurements, have a large benefit to the overall goal of using the remote sensing measurements to infer fluxes.

2.1.2 Atmospheric Carbon Modeling and Data Analysis

Total Costs: $47,300K spanning 2002–2012

An integral component of the GCCP is the application of computer models to understand the various processes of importance and the links between these processes. It is assumed that a wide range of models will be applied to the scientific problems and that these models will be developed and exploited in a variety of universities and research centers. It is also assumed that NASA's Centers will be funded to expand their current research and operational activity to provide support to the GCCP. A combination of competitive funding and base funding is therefore anticipated, whereby the science teams funded through competitive announcements (NRA's) will be expected to liase with the NASA-based teams and to contribute to the development of their models. It is also assumed that the GCCP will build on current NASA and NASA-funded projects; there will be little support for the development of new models, but rather additional support for the development of components for models already in existence.

Model activities will be grouped into four categories, although there are considerable overlaps between them (Figure 9). Modeling and Data Analysis includes Coupled Atmosphere-Land-Ocean Modeling, Carbon Data Assimilation, Data Analysis, and Carbon-climate Predictive Modeling. All categories will be heavily linked to available datasets, especially those proposed or obtained during the course of the GCCP. Cost estimates are presented in Figure 10.

A. Coupled Atmosphere-Land-Ocean Modeling ($32,750K—2002–2012)

The first application will be to use models that focus on limited areas and attempt to model specific processes in considerable detail. Examples are models of the planetary boundary layer or of the mesoscale structure of the atmosphere, which will be applied to understanding the interactions between the biogeochemical cycle and the carbon budget of the free atmosphere. These model studies will draw heavily on the results of past and future observational campaigns, such as the North American Carbon Program (NACP) and any tropical or other missions. The main focus of these models will be to understand the details of processes leading to the observed characteristics of atmospheric carbon species, including emissions, deposition, chemical reactions and transport. Particular emphasis will be needed for simulations of the atmospheric planetary boundary layer and the interactions with the land surface, including emission of trace gases from regions with different types of vegetation.

Anticipated funding for this category is approximately five people for the 10-year duration of the project, to be awarded competitively, with recompetition twice throughout the duration. While funding will remain approximately constant (in real terms), the emphasis of the research will change as new data are collected and as models become more sophisticated. Some component of data assimilation into Planetary Boundary Layer (PBL)-Land Surface Model (LSM)-biogeochemistry models may form a strategic part of this activity.

The first category of modeling also includes the development of coupled global-scale circulation and transport models. This category will have a large competitive component devoted to model development, including transport models, general circulation models including carbon species, and inverse modeling.

Part of this category will require the development and implementation of parameterization schemes into global atmospheric models. Particular attention will be paid to representation of the PBL and its interactions with the land surface and the ocean. It is assumed that research and development for models in use for climate and data assimilation will be funded under separate initiatives, so the work required for the GCCP will draw on those studies. One of the major modeling efforts in the USA is that centered at the National Center for Atmospheric Research (NCAR); this effort involves several other groups, including some universities and collaboration with the NASA Data Assimilation Office (DAO). This modeling effort should be central to the GCCP plans for the reasons given below. It is both the premier national modeling activity, involving many outside groups and providing leverage for linking the GCCP modeling into national efforts, and is also one major application of the global model for data assimilation, where there is already a collaboration between NCAR and the DAO. Alongside the interactive models including carbon species, there would also be space for transport models in this category. These are models where the meteorological data (winds, temperatures, etc.) are provided from meteorological data assimilation systems. Such models can be used to investigate important aspects of the source/sink/transport problem, but must eventually lead to results that enable better interpretation of data through improved understanding of processes.

The competitive research proposals would address fundamental issues in the global modeling of the carbon cycle, especially the structure and diurnal cycle of the PBL and interactions with the land surface and oceans. Other important issues concern the transport of carbon species and their distributions on global scales, for which better understanding of the transport in convective systems (as well as in the PBL) are required. Much work related to the large-scale transport of trace gases is presently supported through NASA's Atmospheric Chemistry Modeling and Analysis Program (ACMAP) and it is assumed that this support will continue to lead to advances, meaning that the development of the large-scale and convective transport models would be a much smaller component of the GCCP. These models would be applied to understanding observed distributions of carbon species.

B. Carbon Data Assimilation ($6,000K—2003–2012)

The second major modeling activity will fund data assimilation research. This includes activities directly in NASA's DAO. All competitively funded research is expected to be linked closely to the DAO activities.

Within the DAO, an additional team will be required to work on the synthesis of different data types with the models. A constant funding level will be needed for this work, although the emphasis will change as the GCCP evolves. Two PI-level scientists will be needed, one to lead the efforts of model/data synthesis, the second to lead the assimilation work. The first of these will be an atmospheric scientist, working with the instrument teams to incorporate the data into the system. This work will begin with the provision of simulated carbon datasets to the instrument teams, which they will use to develop Observing System Simulation Experiments (OSSE); these OSSE's will then be used by the DAO to study data impacts on the assimilation system. A demonstrated impact through these OSSE assimilation experiments should be one of the factors in deciding whether to fund instruments beyond the proof-of-concept stage. As different instruments become operational, this person would lead the group obtaining the data from the instrument teams and liaising with them on the performance of the system. This person would lead a team of 2–3 additional people, each of whom would concentrate on one or two instruments. The second PI-level scientist in the DAO would be responsible for assimilation techniques. This person would develop and apply theoretical techniques, similar to those used in or proposed for the DAO's operational ozone assimilation system. This person would lead a team of about two additional people.

The operational component includes production and analysis of the meteorological data (especially PBL/free atmosphere relationships related to CO_2 transport) in support of the field missions and any other observations. This will support satellite missions as they become operational, providing meteorological data, which will initially be used for 'offline' assimilation. It will evolve into the production side of the CO_2/meteorology system as a fully coupled system is implemented. (There are strong arguments for doing this online because of the importance of temporal resolution in the parameterized processes, but thus will require time to develop.)

The DAO would incur a substantial computational cost for this work. A dedicated supercomputer would be necessary for the development, testing and operation of a comprehensive carbon species assimilation system. Additionally, the support of one system analyst would be required for the duration of the project, with an additional person once operational data are available. These people would be responsible for preparing data and ensuring smooth throughput of the model and data assimilation system in the computing environment.

(Note that it is assumed that the DAO will continue to be funded to perform meteorological analyses of the atmosphere. The costs for this are not included in this budget.)

C. Data Analysis ($4,050K—2003–2012)

The third category of modeling activity is model-based data analysis specifically including inverse modeling for sources and sinks. Techniques need to be developed to exploit the expected coverage and precision of satellite data, which will be very different from current methods that use the sparse, but very accurate, surface data. Data from such scheduled missions as Atmospheric Infrared Sounder (AIRS)/Aqua, Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY)/ENVISAT, and Tropospheric Emission Spectrometer (TES)/Aura will be used initially until CO_2-specific instruments are available. Use of complementary data, CO and CH_4, will also be explored to assist in identifying specific source and sink processes.

D. Carbon-climate Predictive Modeling ($4,500K—2003–2012)

The fourth category of modeling will be the application of global climate models, including representations of atmosphere, oceans and land, to the prediction problem. Direct costs associated with these models, likely to be awarded competitively, but including the possibility that NASA Centers such as Goddard Institute of Space Studies (GISS) or NASA Seasonal to Interannual Prediction Program (NSIPP) (GSFC) will play major roles, should require funding of about three full-time positions per year throughout the duration of the project. Additionally, supercomputing resources will be required.

An assumption inherent in the costing of this category is that the base models used for the computations will be developed elsewhere in research related to the climate problem (the physical processes) and in process models of CCI-related research (sources and sinks, etc., related to carbon species). These costs are thus incremental to NASA-funded climate change studies (possibly hydrological cycle as well). It would be prudent to fund at least two different modeling groups, to help cover uncertainties inherent in climate prediction.

2.2 LAND BUDGET JUSTIFICATION

Total Costs: $108,100K spanning 2002–2012

The activities and associated funding requirements for the land component of the GCCP were developed in consultation with members of the science community, NASA Centers and representatives from other agencies. The GCCP workshops identified a number of science data needs from which activities and costs were derived. The science needs focus on better measurements of biomass, land cover and disturbance and productivity. To achieve improvements in these areas, a number of activities were costed including field studies, technology demonstrations and intercomparisons, algorithm development for existing and future space sensors, and model development. The activities and costs were based on science needs identified by the planning process, some of which are already part of existing NASA programs.

In the near term a primary focus are activities in support of the NACP to be carried out as a coordinated effort among the various agencies represented by the U.S. Global Change Research Program (USGCRP). However, the production of global science products from space platforms is the long-term goal of the Initiative.

The Land Budget includes support of Field Campaigns, starting with the NACP, Algorithm Development and Calibration/Validation, In Situ Instrument and Technology Development, Data Production and Synthesis, Mission Applications and Requirements Modeling, and Integrative Science and Data Analysis (Figure 11). A detailed breakout of the proposed land budget by category and year is presented in Figure 12.

2.2.1. Field Campaigns

Total Costs: $39,400K spanning 2002–2012

A. North American Carbon Program (previously North American Field Campaign)

In support of the USGCRP Interagency-sponsored North American Carbon Program that is currently in the proposal stages, GCCP will contribute science and infrastructure support in 2003 and 2004 in preparation for a first intensive field campaign in the summer of 2004. Three more intensive campaigns are anticipated in fall, winter and spring of 2005. The GCCP proposes to continue field activities during the rest of 2005 and into 2006 at a lower level while vigorously analyzing results from the intensive field campaigns. At the end of 2006 and/or throughout 2007, GCCP will mount another period of intensive field activities.

Going through the cost estimate line by line, infrastructure will cost $5700K total over 6 years including the first year, 2003, of workshops and plan development and publication. Two thousand six infrastructure costs are lower because of reduced field activities in between intensive periods.

Aircraft biomass measurements will focus on a range of biomass conditions for the three following biome types: closed forest, woodland/shrubland, and crop/grassland. Each aircraft campaign involves 40 hours at $3K/hour + $250K for support (L-3 product generation, instrument team support) x 3 biome types = $1100K per campaign. In 2004 we propose 1 campaign, in 2005, 2 campaigns, in 2006, 1 campaign and in 2007, 2 campaigns.

Science teams (modeling, in situ measurements) are shown to have a lower level of funding in 2006, reflecting reduction in field activities.

Aircraft annual costs for 2 methods x 3 biomes x 20 hours x $3K/hour = $400K +$200K for instrument team and product support = $600K/campaign, one campaign each in 2004, 2005 and 2007.

B. Other Field Campaigns

Costs for a subsequent field campaign, possibly in Eurasia and/or the tropics, are also considered. Infrastructure would cost $1000K/year from 2007–2011 and science activities would be $1500K/year from 2007–2012.

We assume that field campaigns will be carried out and supported in conjunction with other agencies/international partners.

2.2.2 Algorithm Development and Calibration/Validation

Total Costs: $15,700K spanning 2003–2012

A. Land cover products ($7,000K—2003–2012)

Existing space-based measurements and systems can provide valuable information about the state of the land surface that has consequences for carbon fluxes. These resources are not being fully exploited for the purpose of characterizing the land carbon cycle and a number of activities are outlined here to address this. The new carbon cycle land cover products will be used as inputs to improved models and better predictions of land surface sources and sinks of carbon.

Land cover change products are to be produced from analysis and synthesis of data obtained from the Landsat Thematic Mapper (TM) archive merged with observations from Advanced Very High Resolution Radiometer (AVHRR), Moderate-Resolution Imaging Spectroradiometer (MODIS), Multi-angle Imaging Spectroradiometer (MISR), IKONOS and other existing satellite data sources. A combination of literature synthesis and forest stand/canopy reflectance modeling is required, with field validation as well, and would lead to the production of an archive of in situ biomass measurements. The development of carbon flux estimates using land cover change products and in situ biomass data archive would be supported through the NRA process.

For costs assume 4 teams x \$250K/year/team = \$1,000K/year x 3 years (2003–2005) = \$3,000K. This effort will be coordinated with and support the North American Carbon Program. Then, for algorithm development, calibration/validation, and data merging in conjunction with automated processing, assume \$500K/year for 2005–2012.

B. Biomass and Biomass Change (\$7,200K—2003–2012)

This effort will test, intercompare, and demonstrate biomass measurement techniques from aircraft and existing and planned space platforms (Geoscience Laser Altimeter System (GLAS), Advanced Land Observing System (ALOS), Vegetation Canopy LIDAR (VCL)). The goal is to prepare an instrument package to support the North American Carbon Program and to serve as a guide in the selection of a future biomass space mission. Three canopy types representing a range of above-ground biomass conditions are to be assessed: dense forest, discontinuous woodlands and continuous grassland, shrubland, and agriculture.

To estimate the cost assume 50 flight hours x \$3K/hour + \$250K for each canopy type. For instrument team support and data processing add \$500K; for ground validation, L-3 data processing and data synthesis = \$900K each. This adds up to a total of \$2700K in 2003.

Calibration/validation and algorithm development in support of new space missions and continued aircraft campaigns including in situ studies and purchase of fine spatial resolution IKONOS-like imagery will require \$500K/year from 2005–2012 except for \$1000K in 2010 to coincide with data acquisition from new biomass missions.

C. Productivity (\$1,500K—2005–2007)

A small continuing effort to improve capabilities to measure productivity from aircraft and space platforms is proposed. This will involve aircraft demonstrations of new methods along with algorithm development and calibration/validation. Costs are estimated to be \$500K/year from 2005–2007.

2.2.3 In Situ Instrument Technology Development

Total Costs: \$4,000K spanning 2003–2012

Support for the development of new technologies for measuring carbon stocks and fluxes is needed for validation of aircraft and space observations as well as for supporting in situ process studies. Novel approaches for measuring below-ground biomass and carbon isotopes are examples. It is envisaged that this activity would comprise two Announcement of Opportunity (AO) cycles, one of six investigations at \$500K each and a second of four investigations at \$250K each.

2.2.4 Data Production and Synthesis

Total Costs: $25,500K spanning 2003–2012

In order to provide routine, consistent, coherent carbon cycle data products it is necessary to establish an infrastructure for systematic processing. In the near term, processing of Landsat data archive spanning 3 decades will be the primary focus but other satellite data sources will be included as they become available. Initially this processing would be done manually but to reduce costs while increasing data volumes more automated processing systems are proposed that need to be initiated in 2003.

For manual processing of the Landsat archive, assume processing of 7000 Landsat triplets (1975, 1990, 2000 data sets) at $1500 per scene triplet. The cost driver is "hand fixing" each scene triplet to take into account location-unique spectral signatures for forest type, regrowth, etc. This results in $1500 x 7000 triplets = $10,500K.

Support for the development and operation of the automated processing system would include four data base specialists, technical support, computer hardware and maintenance, and a principal investigator, at a cost of $275K/year in salaries for the life of the project (2003–2012). Adding equipment, travel, and indirect costs would bring the effort to ~$500K/year.

Support for the production of level-4 biomass/carbon products from new missions begins in 2007 at $500K/year, rises to $1,000K/year in 2008–2010 and drops to $500K/year for 2011 and 2012, for a total of $4,500K. Integrated Data system archive of carbon and ancillary data products is planned at $600K/year for 2003–2012 for a total cost of $6,000K.

2.2.5 Mission Applications and Requirements Modeling

Total Costs: $3,000K spanning 2003–2012

The initiative proposes support for modeling activities specifically aimed at establishing requirements needed to derive useful information from space-based measurements. Models will help define when, where and how accurate measurements need to be. Such information will contributing to the selection and design of new technologies as well as to the production of products from existing sources. A continuous but moderate level of funding for these activities is required at $300K/year for 2003–2012 with a total cost of $3,000K.

2.2.6 Integrative Science And Data Analysis

Total Costs: $20,500K spanning 2003–2012

Besides modeling for measurement requirements (see above), support is needed to improve land surface biogeochemical models and couple them to land/ocean/atmosphere climate models and data assimilation models.

Coupling of land processes to land/ocean/atmosphere system models is expected to cost $500K/year for 2003–2012.

Support for the development of global land carbon cycle models that integrate advances in process understanding are also estimated at $500K/year for 2003–2012.

Land data assimilation at $450K/year for 2003–2012 and Land Science Investigations at $600K/year for 2003–2012 complete the activities, yielding a total cost of $20,500K.

2.3 OCEAN BUDGET JUSTIFICATION

Total Costs: $109,455K spanning 2002–2012

This section and associated budget applies to the oceans component and was reviewed by the other ocean participants in the GCCP workshops, including John Marra (HQ), Mary-Elena Carr (JPL), John Moisan (WFF), Tiffany Moisan (WFF), Frank Hoge (WFF), Watson Gregg (GSFC), Carlos del Castillo (SSC), Mike Behrenfeld (GSFC), and Dick Feely (NOAA). The activities and budget reflect what is thought to be required and makes no assumptions about what might be actually approved or how the program might be consolidated with the existing ocean biogeochemistry program (Figures 13 and 14).

The overall oceans program includes a considerable allocation for field work as well as data analysis and modeling. Historically, the NASA oceans biochemistry program has not invested heavily in field campaigns. Most field work has been for algorithm development and has been supported by mission (SeaWiFS, MODIS, SIMBIOS) calibration and validation programs which are rather limited in scope. On the other hand, the terrestrial and atmospheric programs have undertaken large field campaigns such as First International Satellite Land Surface Project (ISLSCP) Field Experiment (FIFE) and Boreal Ecosystem Atmosphere Experiment (BOREAS). The emphasis of the field work would be on improving coupled model parameterizations of certain processes and on developing better remote sensing algorithms for a number of carbon related quantities, e.g., primary production, export production, dissolved organic matter, particulate organic carbon, and air-sea CO_2 flux. The objective is not to use the in situ measurements to derive estimates of the budgets themselves, but rather to develop the tools and methodologies that would allow estimates based on remote sensing data and models (with remote sensing data assimilation). In fact, it is unlikely that the in situ measurement program alone could be extensive enough to derive accurate ocean carbon budgets, especially in the coastal zone.

Initially, the focus will be on utilization of existing data sets and participation in the NACP that the Interagency Working Group (IWG) will be planning in more detail (goal for completion to be 2006). The North American Carbon Program would presumably include field components in the North Pacific and North Atlantic. To complement the surveys, small annual augmentations for the Hawaii Ocean Time Series (HOT) and Bermuda Atlantic Time Series Study (BATS) time series are included. After that, quantifying the role of the Southern Ocean in the global carbon budget will be a focus (also an IWG objective). Focusing on the Southern Ocean later in the program takes advantage of a more comprehensive satellite capability than will be available in the early years, e.g., atmospheric CO_2 and sea surface salinity (assuming these missions get approved). Additional support for participation in NSF programs like SOLAS (Surface Ocean, Lower Atmosphere Study) is also identified. It is not known at this time when these field programs will occur, so some assumptions about schedule and duration have been made.

Five coastal U.S. sites have been selected for detailed field observations to better understand carbon cycling on the continental shelves and nearshore regions. Each site would have four 1-week cruises during a year with a limited time series site to quantify variability throughout the year. The thinking is that the processes regulating photosynthesis, nutrient cycling, light limitation, carbon chemistry (organic and inorganic), nutrient remineralization, etc., probably differ throughout an annual cycle and with location. The five sites are the Chesapeake Bay/Mid-Atlantic Bight, the Mississippi Delta, the Pacific Northwest (Washington-Oregon), the Bering Sea, and the South Atlantic Bight. Each of these sites is fairly unique. For resource reasons, only one site will be studied in a given year. These observations would also support the North American carbon source/sink study and may allow an extrapolation to most other coastal regimes.

Finally, resources for some laboratory studies and special calibration/validation work that would not be suited for the cruises listed above are costed. Technology development for in situ instruments, platforms, etc., is available in the early years. Coordination with the NASA Small Business Innovative Research (SBIR) program to define GCCP technology focus themes will be pursued. Technology development costs for aircraft instrumentation and satellite missions are carried under a separate GCCP budget category.

Some assumptions about the number of investigators and levels of support required for ocean activities are outlined below.

2.3.1 Open-Ocean Field Studies

Total Costs: $28,900K spanning 2003–2012

This involves collaboration with NOAA and NSF, which provide ship time, air-sea CO_2 flux measurements, and inorganic chemistry. NASA supports five investigators to measure optics, primary production, phytoplankton physiology/adaptation, organic chemistry, and aircraft observations (e.g., pump-probe lidar). Support at either $200K/year (NSF cruises), $300K/year (NOAA North American study open-ocean cruises), or 400K/year (southern ocean cruises) per investigator. Aircraft support is set at $500K (Northern Hemisphere) or $700K (southern ocean studies) per field campaign year.

2.3.2 Coastal Ocean Field Studies

Total Costs: $21,080K, spanning 2003–2012

These studies include ship time at $10K/day, four 1-week cruises/year, 7 investigators to measure optics, primary production, phytoplankton physiology/adaptation, organic chemistry, inorganic chemistry, air-sea CO_2 flux, optics, and aircraft observations. Support is set at $300K/year per investigator and $500K/year for the aircraft program. One-year time series measurements at a coastal site, e.g., buoy, platform, or frequent ship of opportunity, are set at $400K/year.

2.3.3 Algorithm Development

Total Costs: $22,925K, spanning 2002–2012

Aside from the data collection activities, which naturally will include some algorithm development (bio-optical, air-sea flux, atmospheric correction), there will be nine other studies at $150K/year included. Additional funds are identified for calibration and validation of ocean salinity radiometry and particulate profile lidar systems that are under development.

2.3.4 Modeling, Data Assimilation, Process Studies, and Data Analysis

Total Costs: $30,950K, spanning 2003–2012

These activities encompass the following: (1) development coupled physical biogeochemical ocean process models, (2) development of data assimilation methods for ocean biogeochemical data, and (3) the interpretation of in situ, satellite, and ocean model data. Twelve to 17 investigations of these types are supported with more investigations in the later years as more information from satellites and models becomes available. The investigations are costed at $150K each/year.

This includes 12–17 science investigations at $150K/year each. It is envisioned that the GCCP will develop a coupled land-ocean-atmosphere modeling capability that emphasizes satellite carbon (atmospheric, land, and ocean) data assimilation capabilities. This effort would take advantage of the capabilities already being developed by the DAO and the NASA Seasonal-to-Interannual Prediction Program (NSIPP) activities.

2.3.5 Data Production

Total Costs: $4,000K, spanning 2005–2012

It is expected that some retrospective analyses of historical satellite data sets (e.g., Coastal Zone Color Scanner, SeaWiFS, MODIS) will be required as new algorithms and data products are developed. Budgeting for this begins in FY05 when the algorithm development activities are expected to begin bearing fruit. The budget supports the generation of these new products by augmenting the existing data systems (SeaWiFS, MODIS, etc.). $500K/year is allocated for these special processing requirements.

2.3.6 In Situ Instrument Technology Development

Total Costs: $1,600K, spanning 2003–2006

These funds help support advanced in situ instrument development needed to improve the variety and quality of biological, chemical, and optical data needed for algorithm development, post-launch satellite calibration, and product validation. The allocation is a modest $400K/year for 4 years early in the initiative. It is hoped that these developments can be co-funded by other agencies such as NOAA and NSF, and that in the out-years, these activities can be orchestrated through the SBIR and other technology programs.

3.0 ENGINEERING IMPLEMENTATION

3.1 RESOURCE ESTIMATION

The project formulation and systems engineering team developed space and aircraft mission costs by utilizing existing data bases and cost estimating relationships. A full life cycle costing (LCC) methodology was adopted for all mission costs. LCC captures the total cost for all mission elements (launch, flight, and ground) required to formulate, implement, and operate each mission and also to deliver the required data to the science and user communities. For purposes of costing, GCCP was treated as a stand-alone program with its own funding for mission specific technology. Other programmatic assumptions included an open data policy with traditional roles and responsibilities for NASA Headquarters, GSFC, other NASA Centers, government agencies, universities, and industry. A roadmap of activities, missions, and critical dependencies by discipline and year are shown in Figure 15. Because some of the missions involve lidar systems, which present technology challenges and will require development investments, a history of lidar systems is provided in Figure 16 and serves as the starting point for lidar technical and cost evaluations.

3.2 STRATEGY

Initial cost estimates were prepared for a baseline set of five missions and several options. The baseline set included a pathfinder atmospheric CO_2 mission, an ocean carbon mission like SeaWiFS with better spatial resolution and additional ultraviolet and fluorescence bands, a low-density biomass/coastal ocean mission, a high-density biomass mission consisting of a radar and lidar combination, and an advanced atmospheric CO_2 mission (Figures 17–21). These missions were intended to be generic and to serve only as a basis for providing costs to scope the program. It is recognized that a specific implementation technique for making each critical carbon cycle measurement can only be determined after a concerted concept definition and formulation phase as directed by NASA Program Guideline (NPG) 7120.5A. Nevertheless, for purposes of program budget planning, it was necessary to develop very basic concepts with associated mass, power, and data rate estimates so that existing cost-estimating relationships could be employed. Competition and the peer review process will determine what mission concept is ultimately selected.

Two additional missions, considered critical dependencies for the carbon cycle work, were added to the program after this study was completed. An aerosols mission, previously included in the Climate Change Research Program, is now closely allied to the Carbon Cycle Initiative (Figure 22). Second, the Vegetation Canopy Lidar (VCL) will be launched a little later than planned and is considered a precursor to the high-density biomass lidar. These two missions were therefore not costed as part of the originally proposed program, but an estimate for the aerosols mission was later developed and is included here.

3.3 SPACE MISSION COSTING

A mission cost template was developed that included the following elements of cost: technology development, preformulation, formulation, project management, instrument design and development, spacecraft design and development, mission systems integration and testing, launch vehicle, ground and data system accommodations, mission operations and data analysis, post-launch calibration and validation, contingency, and fee. The costs for preformulation, formulation, and project management were based on estimates for expected staff salaries and definition studies. Instrument design and development costs for most missions were generated by the GSFC Resource Analysis Office (RAO) based on information provided by the study team and using a parametric model (MICM) that was constructed from a data base of similar instruments. The lower limit assumed a 3-year mission and a 3-year implementation phase. The upper limit assumed a 5-year mission and 4-year implementation phase. All instruments were costed in the protoflight mode with an engineering model included for the higher risk laser/lidar systems. The cost of a P-band synthetic aperture radar for the high-density biomass mission was taken from previous Earth science mission studies. Technology development was also estimated by RAO considering the effort required to bring an instrument from its current technology readiness level (TRL) to a level of 6 by the time of mission approval (implementation phase). A spacecraft cost range was provided by the GSFC Rapid Spacecraft Development Office (RSDO) after an analysis was performed to ensure that there were candidate buses in their catalog that could accommodate the proposed scientific instruments. Launch vehicle/service costs were supplied by the GSFC Access To Space (ATS) group. Ground system development, mission operations, and data analysis costs were estimated by the GSFC Networks and Mission Services Division. Post-launch calibration and validation costs were provided by the science team. Life cycle costs and cost profiles were then compiled for each mission in the baseline set.

3.4 SPACE MISSION PROFILES

All space and aircraft mission cost profiles for the baseline missions (Figure 23) are presented in Figures 25–31, as well as the formulas used for spreading the cost over years (Figure 24). These costs are presented in current year dollars (2001$) instead of real year dollars because of programmatic uncertainty about the order of the missions and their actual launch dates at this early stage.

3.5 SPACE MISSION OPTIONS

In addition to the baseline mission set, four optional mission sequences, identified below, were also considered during the GCCP study. These options included a reduced mission frequency as well as modifications to the proposed flight program and adjustments to cost that could be made as a result of a successful launch of VCL in the near term and/or an ESSP mission selection favorable to carbon cycle science.

Option 1: Reduced Mission Frequency and No VCL Launch

- Pathfinder Atmospheric CO_2/Ocean Carbon
- High Density Biomass
- Advanced Atmospheric CO2

Option 2: Successful VCL Launch

- Pathfinder Atmospheric CO_2/Ocean Carbon
- Advanced Atmospheric CO_2
- High Density Biomass

Option 3: Early ESSP Carbon Mission Selection and No VCL Launch

- Pathfinder Atmospheric CO_2 (ESSP)
- Ocean Carbon
- High Density Biomass
- Advanced Atmospheric CO_2

Option 4: Early ESSP Carbon Mission Selection and Successful VCL Launch

- Pathfinder Atmospheric CO_2 (ESSP)
- Ocean Carbon
- Advanced Atmospheric CO_2
- High Density Biomass

Costs for Options 1 through 4 are presented in Figures 32–35. The total costs for Options 2 and 4 are quite similar to 1 and 3, respectively, since the difference involves a reordering of the High Density Biomass and Advanced Atmospheric CO_2 Missions based on a successful VCL launch.

3.6 AIRCRAFT MISSION COSTING

Costs for aircraft missions were estimated based on discussions with various scientists and included missions in support of the pathfinder and advanced atmospheric CO_2 measurements as well as the low- and high-density biomass imaging missions. In addition, there were two stand-alone aircraft missions, not associated with a space mission: an ocean bicarbonate lidar and an ocean particulate lidar. Costs presented are for initial demonstration of instruments dedicated only to aircraft operations and for demonstrating the performance of an aircraft version of an intended spaceborne instrument. Aircraft flights in support of post-launch calibration/ validation, spacecraft underflight, and extended science field campaigns are included separately in the science discipline budgets. The aircraft missions that were costed are listed in Figure 36.

Only new aircraft instruments and accompanying integration and test flights were estimated in this section. Aircraft instrument costs were estimated by selecting an aircraft instrument that could represent any of the known candidates for making the measurement. Actual instruments for field campaigns, and calibration/ validation of carbon cycle space instruments after launch will be determined at the time of deployment. The estimates for three classes of aircraft missions—measurement validation of carbon cycle space instruments and future space measurement concepts; field campaigns; and post-launch calibration/validation of carbon cycle space instruments—are described in the science discussions in this document.

The principal investigator's estimate for the design and development of new aircraft instruments included ground integration and test, management, data handling/processing equipment, and interface support fixtures development. System integration and test flight costs include any special thermal/vacuum or large scale optical modifications. System integration and test flight costs were estimated at 20 or less flight hours, taking place over 2 weeks and were based on the subsidized cost per flight hour. Subsidized costs per flight hour were obtained from aircraft project offices and actual costs of past missions. Flight crew and science team man-hours were calculated using the principal investigator's man-hour estimates and the standard in-house cost per man-hour. Travel was estimated using standard in-house cost and past mission spreadsheets. Costs to develop ground processing for science operations were estimated by the principal investigator. The rest of the costs are included in center, science, and spacecraft project data operations. Contingency was added to the total ensuring adequate resources.

Costs for the aircraft missions as well as a summary of costs are shown in Figures 37–45.

3.7 TECHNOLOGY COSTING

For each mission, technology readiness levels, as defined in Figure 46, were estimated for the various components and were used to derive an overall TRL for the mission (Figures 47–50). (Pathfinder CO_2 and Ocean Carbon are already considered to be technologically ready.) This information was used to develop the cost of bringing each mission to the required TRL by the time of approval. In addition, specific areas in need of technology development were identified by the appropriate instrument teams and by the participants at the workshop (Figure 51). The costs and cost profiles associated with both the mission specific and common technology development are shown in Figures 52–53. Several programs within NASA will be leveraged to develop technologies directly applicable to carbon cycle science. These are described below.

New Millennium Program (NMP)—emphasizes the development of enabling and enhancing instrument and spacecraft technologies that require on-orbit demonstration/validation before implementation on a NASA flight program.

Earth Systems Science Pathfinder (ESSP)—a program dedicated to performing explorer-class missions that provide answers to key Earth science research questions.

Instrument Incubator (IIP)—identifies, develops and, where appropriate, demonstrates new measurement technologies which reduce the risk, cost, size, and development time of Earth-observing instruments, and enables new Earth-observation measurements.

Advanced Component Technology—seeks to further the development of advanced components that enable innovative instrument and platform system designs (formerly Advanced Technology Initiatives Program (ATIP)).

Advanced Information Systems Technology—identifies, develops and, where appropriate, demonstrates advanced information system technologies which reduce the risk, cost, size, and development time of OES space-based and ground-based information systems, increases the accessibility and utility of Earth science data, and enables new Earth-observation measurements and information products.

Computational Technologies—demonstrates the potential afforded by teraFLOPS (trillion floating-point operations per second) performance to further our understanding and ability to predict the dynamic interaction of physical, chemical, and biological processes affecting the solar-terrestrial environment.

Advanced Platform Technology—provides technologies that will significantly increase capabilities and reduce costs for Earth science platforms, as well as enabling new missions with revolutionary concepts.

Small Business Innovative Research—a broad Government-wide initiative managed by the Small Business Administration that seeks to foster cooperative research and development.

Small Business Technology Transfer Research—draws upon the talents of small, innovative businesses in partnership with a research institute to convert research investments into new commercial technologies.

3.8 COST SUMMARY

The total cost profiles for the science and engineering implementation of the baseline mission set are presented in Figure 54. These costs include all science activities, space and aircraft missions, and technology development and are presented in current year dollars (2001$) instead of real-year dollars because of programmatic uncertainty about the order of the missions and their actual launch dates at this early stage.

4.0 ACRONYMS

A/C Aircraft

A/D Analog to Digital

ACMAP Atmospheric Chemistry Modeling and Analysis Program

AIRS Atmospheric Infrared Sounder

AIST Advanced Information Systems Technology

ALOS Advanced Land Observing System

AO Announcement of Opportunity

ASTER Advanced Spaceborne Thermal Emission and Reflection Radiometer

ATIP Advanced Technology Initiatives Program

ATMS Advanced Technology Microwave Sounder

ATS Access To Space

AVHRR Advanced Very High Resolution Radiometer

AVIRIS Advanced Visible and Infrared Imaging Spectrometer

BATS Bermuda Atlantic Time Series

BM Biomass

BOREAS Boreal Ecosystem-Atmosphere Study

CCP Carbon Cycle Program

CDOM Colored Dissolved Organic Material

CNES Centre National D'Etudes Spatiales

CrIS Cross-track Infrared Sounder

DAAC Distributed Active Archive Center

DAO Data Assimilation Office

DIAL Differential Absorption Lidar

DIC dissolved inorganic carbon

DOC dissolved organic carbon

EOS Earth Observing System

ESE Earth Science Enterprise

ESSP Earth System Science Pathfinder

ESTO Earth Science Technology Office

ETM+ Enhanced Thematic Mapper Plus

FIFE First ISLSCP (International Satellite Land Surface Climatology Project) Field Experiment

fPAR fraction of photosynthetically active radiation

FPI Fabry-Perot Interferometer

FTE Full Time Equivalent (One man year)

FY Fiscal Year

GCCP Global Carbon Cycle Plan

GCM General Circulation Model

GCOS Global Climate Observing System

GISS Goddard Institute for Space Studies

GEOS Study of sedimentary layer of oceans (Russian)

GLAS Geoscience Laser Altimeter System

GPS Global Positioning System

GSFC Goddard Space Flight Center

HIRDLS High Resolution Dynamics Limb Sounder

HOT Hawaii Ocean Time Series

HQ Headquarters

ICESat Ice, Cloud and land Elevation Satellite

IIP Instrument Incubator Program

IKONOS ancient Greek word for image (not an acronym)

IMDC Integrated Mission Design Center

ISAL Instrument Synthesis and Analysis Laboratory

ISLSCP International Satellite Land Surface Climatology Project

IWG Interagency Working Group

JER-1 Japanese Earth Resources -1

JGOFS Joint Global Ocean Flux Study

JPL Jet Propulsion Laboratory

LAI leaf area index

LaRC Langley Research Center

LBA Largescale Biosphere atmosphere experiment in Amazonia

LC Land Cover

LCC Life Cycle Cost

LEO Low Earth Orbit

Lidar Light Detection and Ranging

LITE Lidar In-space Technology Experiment

LPT Low Power Transmitter

LSM Land Surface Model

MAB Mid Atlantic Bight

MAPS Measurement of Atmospheric Pollution from Satellites

MBLA Multi-Beam Laser Altimeter

MERIS Medium-Resolution Imaging Spectrometer

MICM Multi-Instrument Cost Model

MISR Multi-angle Imaging Spectroradiometer

MLS Microwave Limb Sounder

MODIS Moderate-Resolution Imaging Spectroradiometer

MOPITT Measurements of Pollution in the Troposphere

NACP North American Carbon Program

NAFC North American Field Campaign, now included in NACP

NASA National Aeronautics and Space Administration

NCAR National Center for Atmospheric Research

NCCI NASA Carbon Cycle Initiative; NASA Climate Change Initiative

NMHC non-methane hydrocarbons

NOAA National Atmospheric and Oceanic Administration

NPG NASA Program Guideline

NMP New Millennium Program

NPOESS Near Polar Orbiting Earth Satellite System

NPP NPOESS Preparatory Project

NPP net primary productivity

NRA NASA Research Announcement

NSF National Science Foundation

NSIPP NASA Seasonal to Interannual Prediction Program

OES Office of Earth Sciences

OSSE Observing System Simulation Experiment

PAR Photosynthetically Active Radiation

PARASOL Polarization and Anisotropy of Reflectances for Atmospheric Science coupled with Observations

PBL Planetary Boundary Layer

PI Principal Investigator

PIC Particulate Inorganic Carbon

POC Particulate Organic Carbon

RAO Resource Analysis Office

RSDO Rapid Spacecraft Development Office

SAGE Stratospheric Aerosol and Gas Experiment

SAR Synthetic Aperture Radar

SBIR Small Business Innovation Research

SCIAMACHY Scanning Imaging Absorption Spectrometer for Atmospheric Cartography SeaDAS SeaWiFS Data Analysis System

SEASAT Sea Satellite

SeaWiFS Sea-viewing Wide Field-of-view Sensor

SIMBIOS Sensor Intercomparison and Merger for Biological and Interdisciplinary Ocean Studies

SIR Shuttle Imaging Radar

SLA Shuttle Laser Altimeter

SPARCLE Space Readiness Coherent Lidar Experiment

SNR Signal to Noise Ratio

SOLAS Surface Ocean, Lower Atmosphere Study

SOLVE SAGE III Ozone Loss and Validation Experiment

SSC Stennis Space Center

SSH sea surface height

SSS sea surface salinity

SST sea surface temperature

SSW sea surface winds

STTR Small Business Technology Transfer Research

SWIR Short Wave Infrared

TES Tropospheric Emission Spectrometer

TM Thematic Mapper

TM Technical Memorandum

TRL Technology Readiness Level

TRWIS TRW Imaging Spectrometer

USGCRP US Global Change Research Program

VCL Vegetation Canopy Lidar

VIIRS Visible and Infrared Imaging Radiometer Suite

VHRR Very High Resolution Radiometer

VNIR Visible & Near Infrared

WCRP World Climate Research Program

WFF Wallops Flight Facility

WMO/UNEP World Meteorological Organization/United Nations Environment Program

5.0 FIGURES

Figure 1. PROPOSAL DEVELOPMENT PROCESS

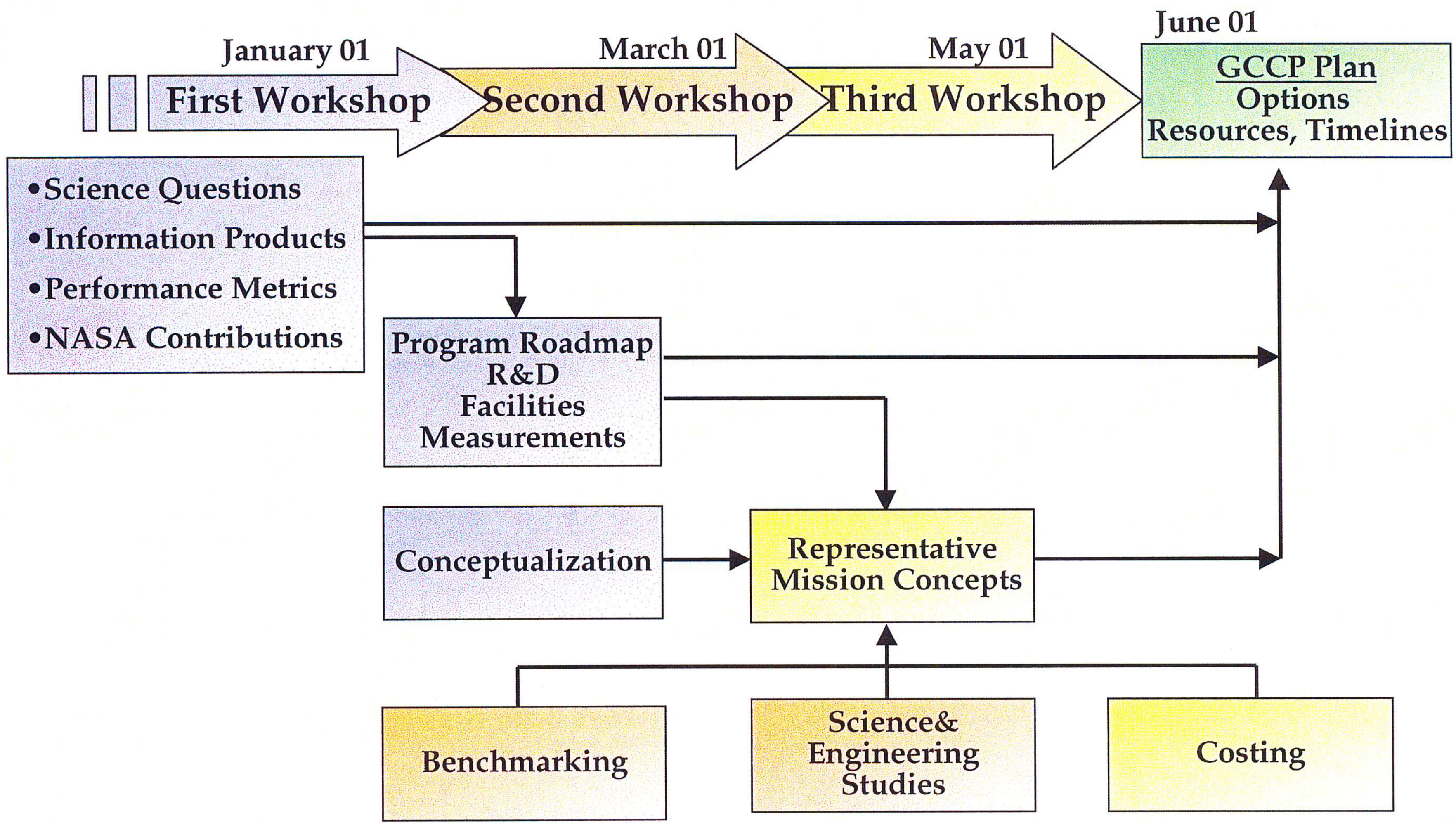


Figure 2. Study Process Flow

The methodology adopted for the GCCP study is illustrated in the diagram below. Program goals and objectives are identified. Discipline science teams determine the type, location, and frequency of measurements to be made. From this information, the engineering team develops concepts for flight missions that achieve desired results. Full life-cycle costs are then estimated.

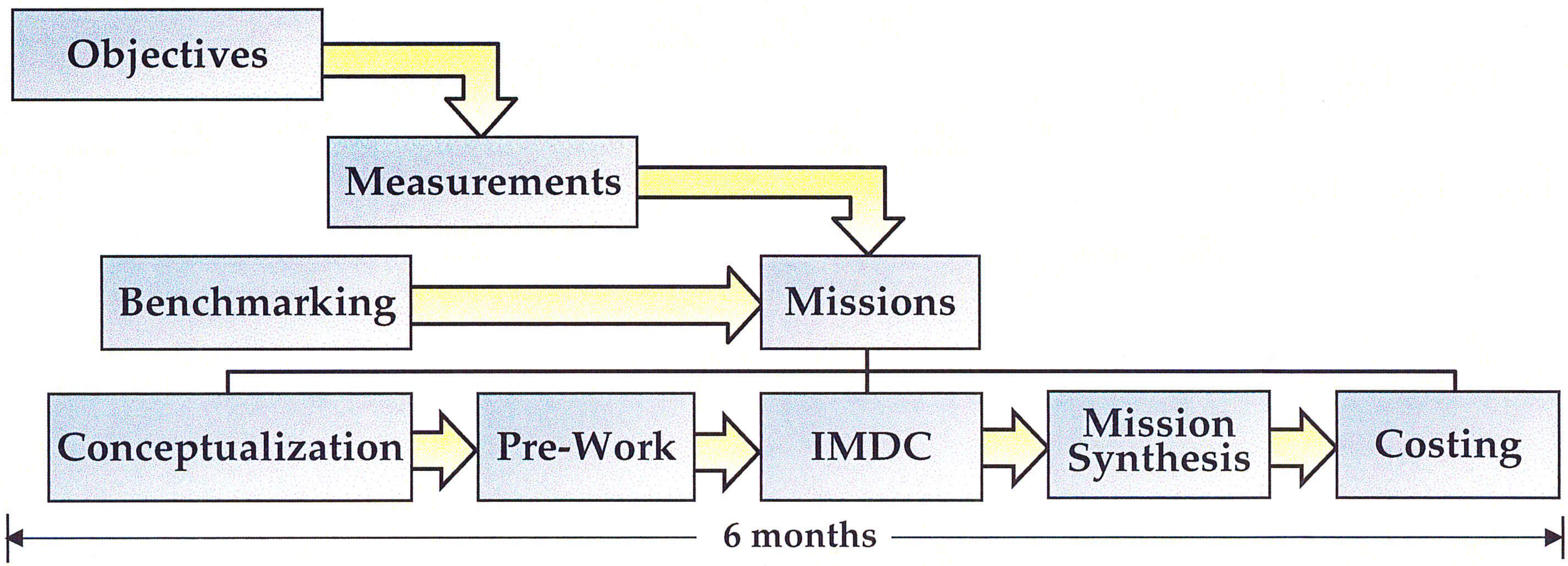


Figure 3. Science Activity Roadmap

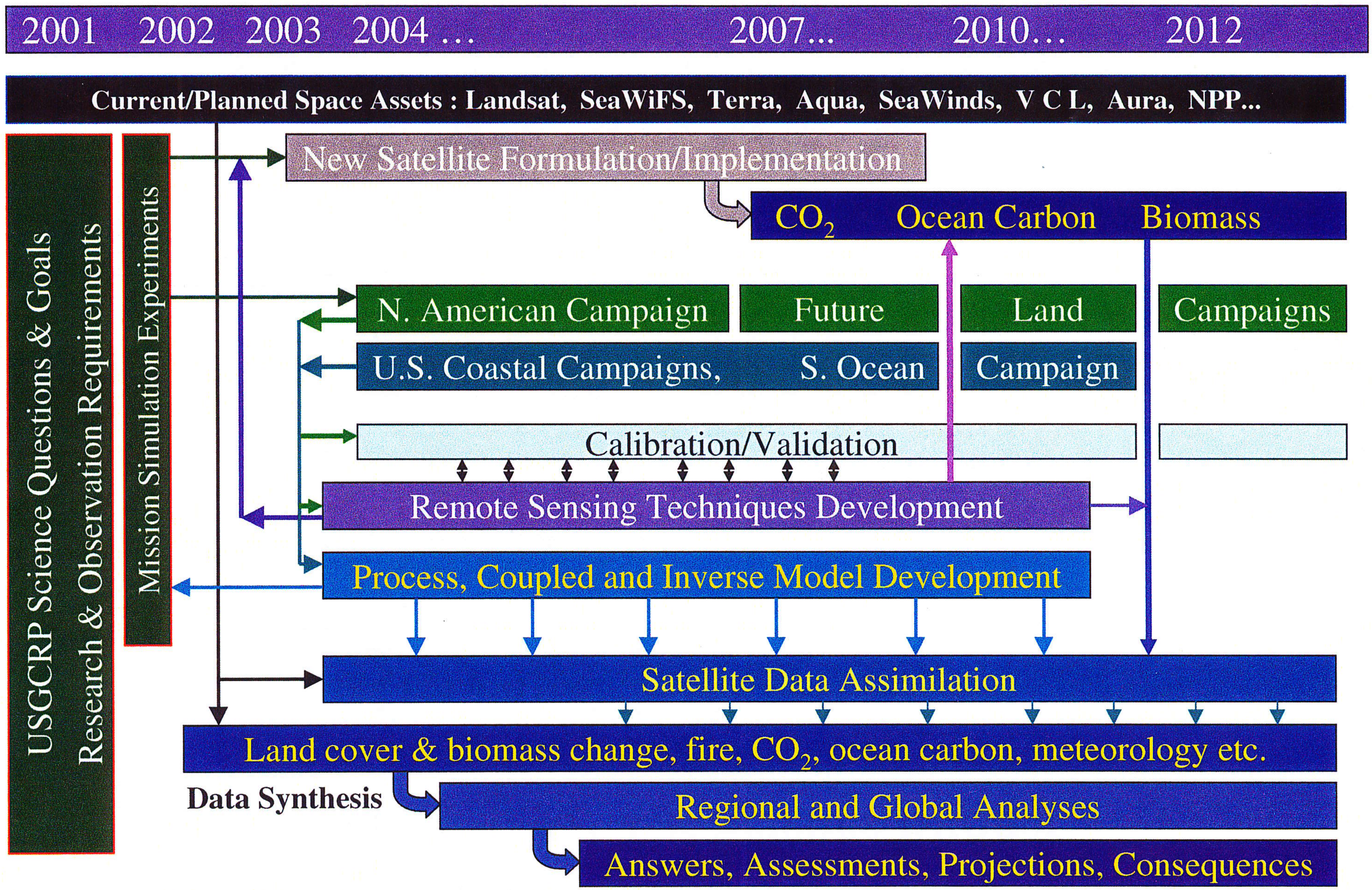


Figure 4. GCCP Science Budget

	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	Total ($M)
Field Campaigns ($M)	0.3	6.78	24.73	25.78	18.48	22.38	16.78	12.95	11.55	15.3	14.1	169.13
Land	100	500	6700	7900	3900	7800	2500	2500	2500	2500	2500	
Atmospheres	200	2400	10150	10300	6700	9200	9200	4850	3650	7700	9200	
Oceans	0	3380	6580	6580	6580	4580	4580	5100	5100	5100	2400	
Field Support	0	500	1300	1000	1300	800	500	500	300			
Algorithm Development /Cal Val	0.45	7.8	4.7	6.15	6.6	4.45	3.775	4.675	5.175	3.175	3.175	50.13
Land	0	3700	1000	2500	1500	1500	1000	1000	1500	1000	1000	
Atmospheres	150	1050	650	800	2400	900	750	1950	1950	450	450	
Oceans	300	3050	3050	2850	2700	2050	2025	1725	1725	1725	1725	
In Situ & A/C Inst/Tech Dev ($M	0.1	6.85	7.35	5.55	2.2	1.05	0.8	0.35	0.25	0.25	0	24.75
Land	0	500	1000	1000	800	300	300	100	0	0	0	
Atmospheres	100	950	950	1150	1000	750	500	250	250	250	0	
Oceans	0	400	400	400	400	0	0	0	0	0	0	
A/C		5000	5000	3000								
Data Production and Synthesis ($	0	6.1	6.1	1.6	1.6	2.1	2.6	2.6	2.6	2.1	2.1	29.50
Land	0	6100	6100	1100	1100	1600	2100	2100	2100	1600	1600	
Atmospheres	0	0	0	0	0	0	0	0	0	0		
Oceans	0	0	0	500	500	500	500	500	500	500	500	
Modeling/Data Assim/Sys Sim ($	0.25	9.5	10.15	10.65	12.25	12.95	12.1	12.85	12.65	12.65	12.25	118.25
Land	0	1750	1750	1750	1750	1750	1750	1750	1750	1750	1750	
Atmospheres	250	4400	4550	4550	4550	4550	4400	4250	4050	4050	3650	
Oceans	0	1450	1450	1450	1850	1850	1850	1850	1850	1850	1850	
Computation	0	1900	2400	2900	4100	4800	4100	5000	5000	5000	5000	
Science Investigations ($M)	0	1.95	1.95	1.95	2.55	2.55	2.55	2.55	2.55	2.55	2.55	23.70
Land	0	600	600	600	600	600	600	600	600	600	600	
Atmospheres	0	300	300	300	450	450	450	450	450	450	450	
Oceans	0	1050	1050	1050	1500	1500	1500	1500	1500	1500	1500	
Program Coord. ($M)	0.625	1.262	1.262	1.262	1.262	1.262	1.262	1.262	1.262	1.262	1.262	13.25
Summary ($M)												428.70
Land	0.1	12.65	16.15	13.85	8.85	13.25	7.95	7.95	8.45	7.45	7.45	104.10
Atmospheres	0.6	8.15	15.65	15.95	14.1	15.1	14.8	11.5	10.1	12.65	13.75	132.35
Oceans	0.3	8.93	12.13	12.43	13.13	10.48	10.455	10.675	10.675	10.675	7.975	107.86
Science Support	0.725	10.512	12.312	10.712	8.862	7.912	6.662	7.112	6.812	6.512	6.262	84.40
Total Science	1.725	40.242	56.242	52.942	44.942	46.742	39.867	37.237	36.037	37.287	35.437	428.70

	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Field Studies	0.3	6.78	24.73	25.78	18.48	22.38	16.78	12.95	11.55	15.3	14.1
Algorithm Dev.	0.45	7.8	4.7	6.15	6.6	4.45	3.775	4.675	5.175	3.175	3.175
In Situ/AC Inst. Dev.	0.1	6.85	7.35	5.55	2.2	1.05	0.8	0.35	0.25	0.25	0
Data Proc./Synthesis	0	6.1	6.1	1.6	1.6	2.1	2.6	2.6	2.6	2.1	2.1
Modeling/Assimilation	0.25	9.5	10.15	10.65	12.25	12.95	12.1	12.85	12.65	12.65	12.25
Science Investigations	0	1.95	1.95	1.95	2.55	2.55	2.55	2.55	2.55	2.55	2.55
Program Coordination	0.625	1.262	1.262	1.262	1.262	1.262	1.262	1.262	1.262	1.262	1.262
Total	428.7										

Figure 5. Total GCCP Science Budget by Year (FY02-FY12) (2001 M$)

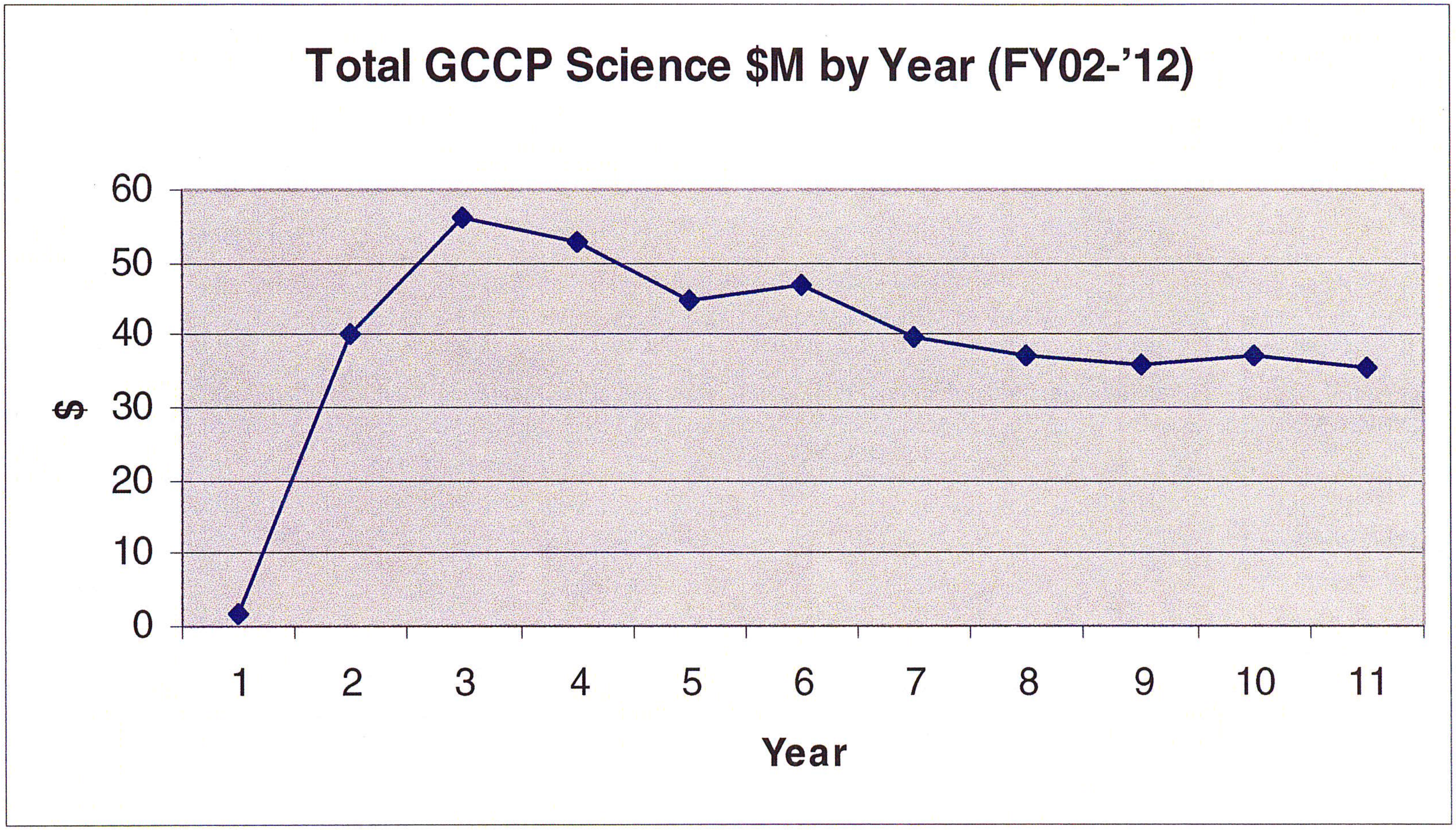


Figure 6. GCCP Science Costs by Discipline (FY02-FY12) (2001 M$)

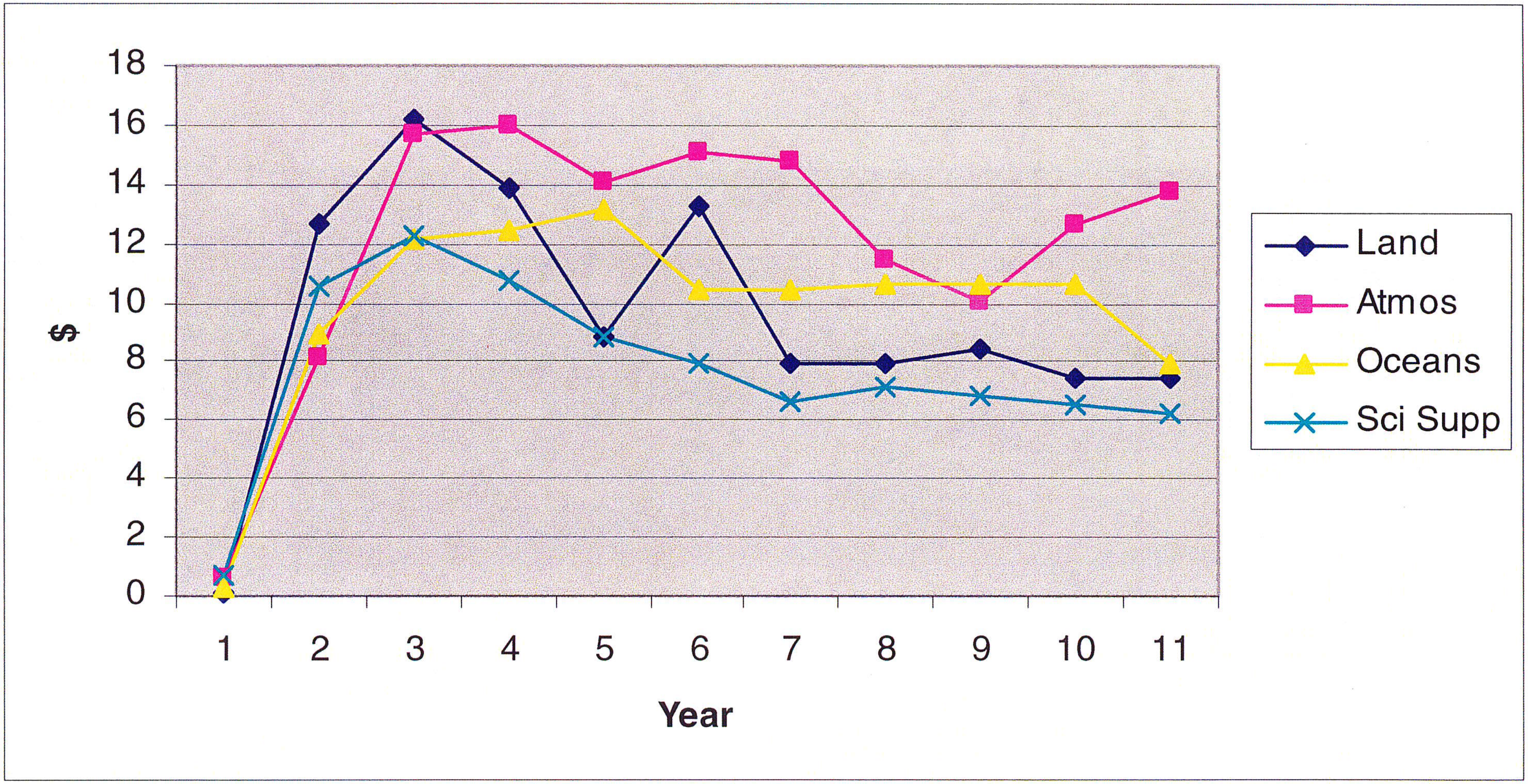


Figure 7. GCCP Science Costs by Activity (FY02-FY12) (2001 M$)

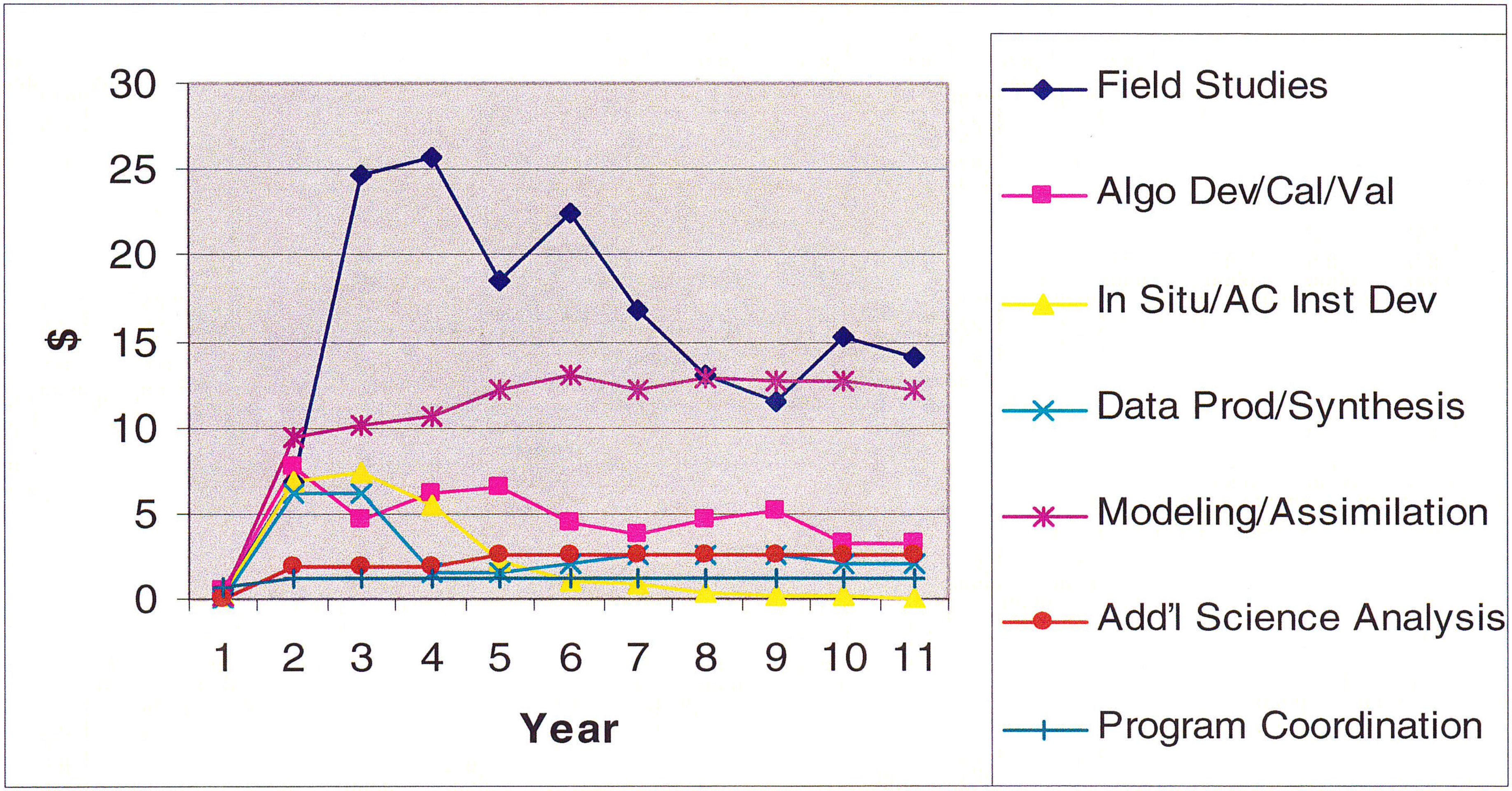
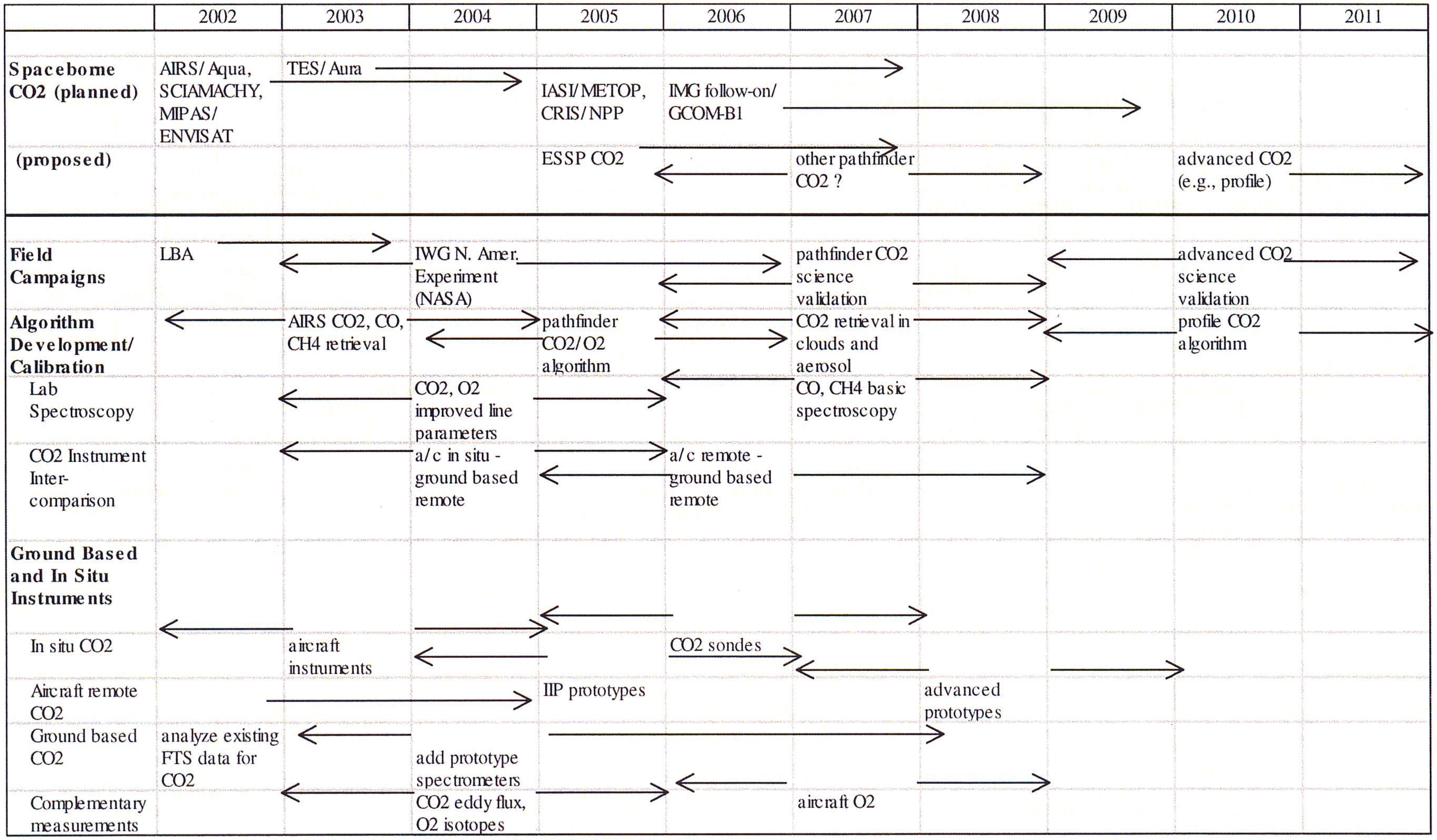
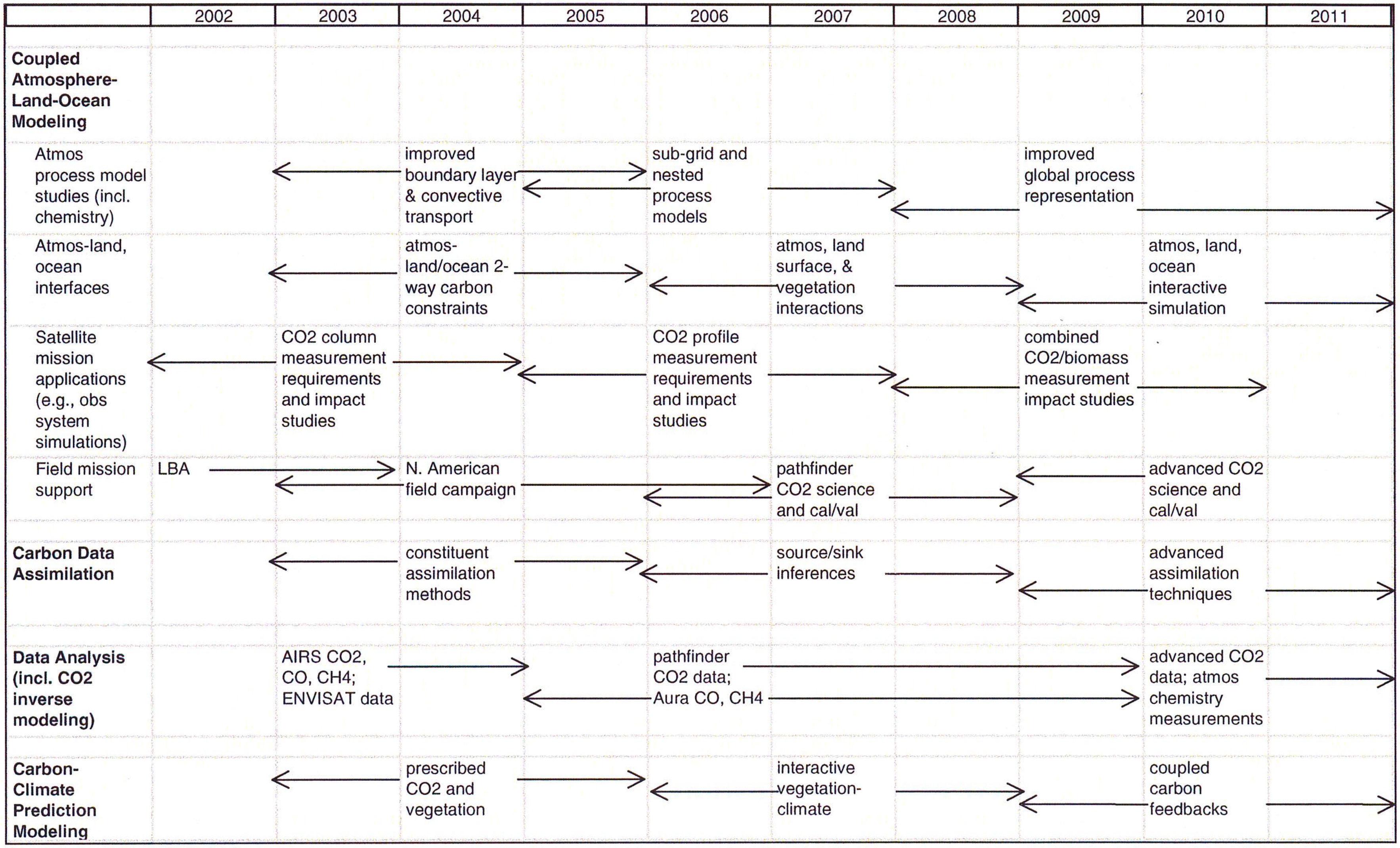


Figure 8. Atmospheric Carbon Measurement Activities



Note: Arrows are meant to represent peak activity levels over time.

Figure 9. Atmospheric Carbon Modeling and Data Analysis



Note: Arrows are meant to represent peak activity levels over time.

Figure 10. GCCP Atmospheres Budget (2001 K$)

Measurement Activities	Detail / TOPIC	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	TOTAL
													91200
Field Campaigns													***54900***
Instrument Team Workforce	50% NAFC, 12-15 teams	100	1500	3100	3100	2400	2100	2100	2100	2400	2400	2400	23700
Flight Hours/Infrastructure	2/1 DC8, 2 Citations, 10 Cessnas			3800	3800		3000	3000			3000	3000	19600
Travel, shipping	50% instr team + crew			1800	1800		1500	1500			1500	1500	9600
Aircraft Intercomparison						2000							2000
Algorithm Development/ Cal Val													***11500***
Retrieval Algorithms	150/group	150	300	300	450	450	450	300	300	300	300	300	3600
Lab Spectroscopy	100/group		200	200	200	300	300	300					1500
CO2 Intercalibration	continuous light aircraft profiles/ non-campaign years		550	150	150	1650	150	150	1650	1650	150	150	6400
Ground Based and In Situ Instruments													***24800***
In Situ CO2	construction; deploy in campaigns & with remotes	100	300	300	250	250	250						1450
Ground Based Remote CO2	construction		250	250	500	500	250	250					2000
Aircraft Remote CO2	operation and data analysis	100	900	900	900	900	1700	1700	1700	200	200	1700	10900
	deployment only; construction in flight tech devel			400	400	800	300	300	600	600	300	300	4000
	workforce, data analysis: $150-300K/group			150	300	600	600	600	450	450	300	300	3750
Complementary Measurements	design, construction, and testing; deploy in campaigns		400	400	400	250	250	250	250	250	250		2700
Modeling and Data Analysis													***47300***
Coupled Atmos-Land-Ocean Modeling	150/FTE Scientist												***32750***
Atmospheric Process Model Studies	community		750	750	750	750	750	750	750	750	750	750	7500
	project/DAO		450	450	450	450	450	450	450	450	450	450	4500
Atmos-Land, -Ocean Interfaces	2 FTE each for Land-Atmos and Ocean-Atmos		600	600	600	600	600	600	600	600	600	600	6000
Satellite Mission Applications	community		450	450	450	450	450	450	300	300	300		3600
	project/DAO	100	450	450	450	450	450	300	300	100	100		3150
Field Mission Support	community		300	450	450	450	450	450	450	450	450	450	4350
	project/DAO, 1 FTE+2 support	150	350	350	350	350	350	350	350	350	350	350	3650
Carbon Data Assimilation	community		300	300	300	300	300	300	300	300	300	300	*3000*
	project/DAO		300	300	300	300	300	300	300	300	300	300	*3000*
Data Analysis			300	300	300	450	450	450	450	450	450	450	*4050*
Carbon-Climate Prediction Modeling			450	450	450	450	450	450	450	450	450	450	*4500*
													138500
TOTAL:		*700*	*9100*	*16600*	*17100*	*15100*	*15850*	*15300*	*11750*	*10350*	*12900*	*13750*	
	Field Campaigns	200	2400	10150	10300	6700	9200	9200	4850	3650	7700	9200	73550
	Algo. Dev./CalVal	150	1050	650	800	2400	900	750	1950	1950	450	450	11500
	In Situ Inst./Tech. Dev.	100	950	950	1150	1000	750	500	250	250	250	0	6150
	Data Production & Synthesis	0	0	0	0	0	0	0	0	0	0	0	0
	Model/Data Asym/Sys Sim	250	4400	4550	4550	4550	4550	4400	4250	4050	4050	3650	43250
	Science Investigations	0	300	300	300	450	450	450	450	450	450	450	4050
													138500

Figure 11. NASA GCCP Land Activities

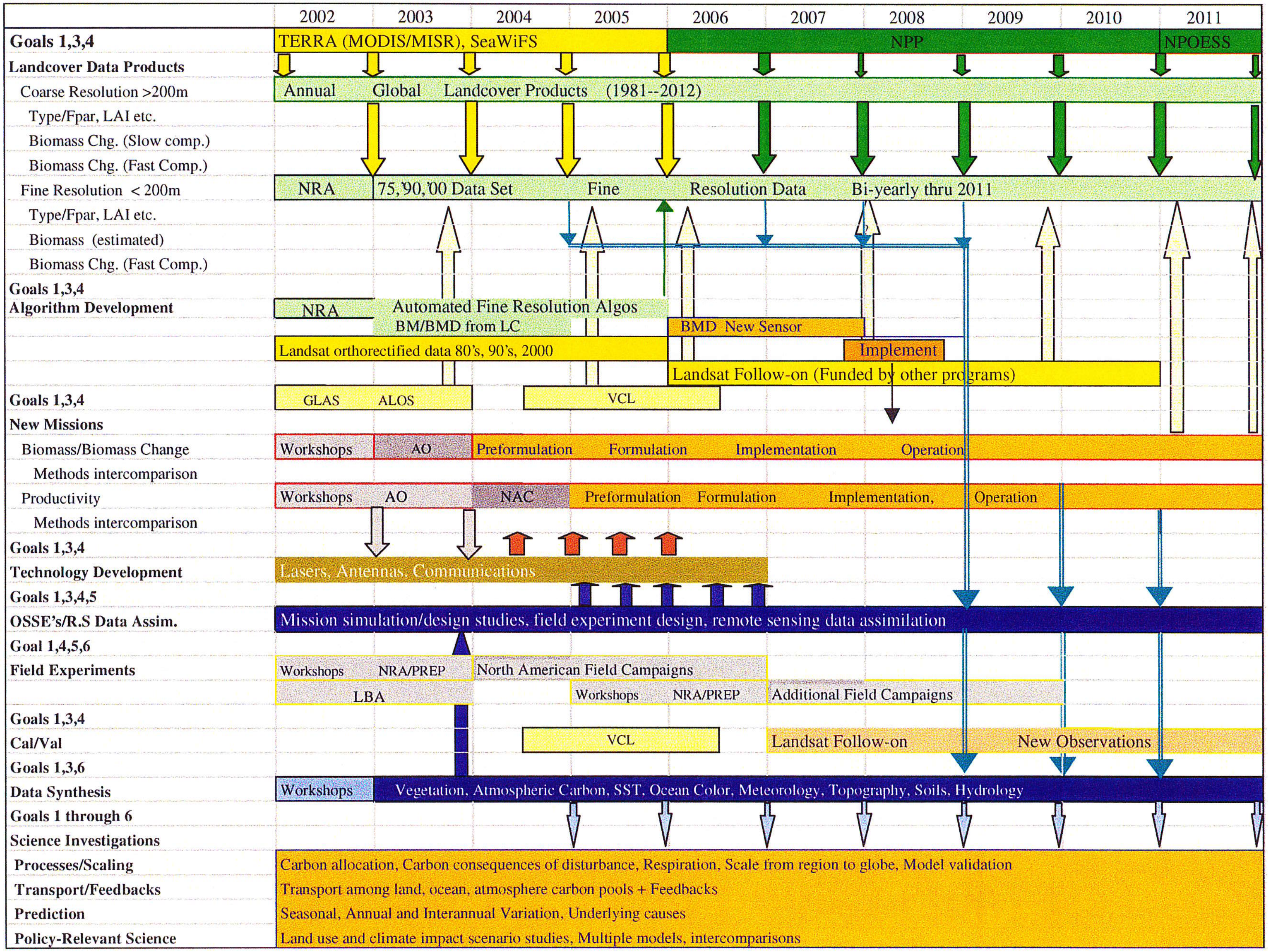


Figure 12. GCCP Land Budget (2001 K$)

CCI Land Budget	02	03	04	05	06	07	08	09	10	11	12	Total
Field Campaigns												
N. American												
Infrastructure	100	500	1500	1600	500	1500						5700
Aircraft deployment - biomass L-3 products			1100	2200	1100	2200						6600
Process studies and modeling			3000	3000	2000	3000						11000
landcover remote sensing science			500	500	300	500						1800
Aircraft deployment - productivity			600	600		600						1800
												0
												0
Eurasia/Tropical ??												0
Infrastructure							1000	1000	1000	1000	1000	5000
Science activities (process studies &modeling)							1500	1500	1500	1500	1500	7500
												0
Algorithm Development/Cal/Val												
Landcover products												0
derived from satellite archive and inventories		1000	1000	1000								3000
derived from automated processing and merging				500	500	500	500	500	500	500	500	4000
Biomass												0
Aircraft/satellite demo & intercomparison		2700										2700
products from new biomass sensors- A/C & space				500	500	500	500	500	1000	500	500	4500
Productivity												0
products from new productivity measurements				500	500	500						1500
												0
In situ instrument tech development												0
carbon stocks and fluxes		500	1000	1000	800	300	300	100				4000
												0
Data Production and Synthesis												0
Landcover products												
manual processing		5000	5000									10000
Automated Processing system		500	500	500	500	500	500	500	500	500	500	5000
Biomass Products												0
L-4 products from new missions						500	1000	1000	1000	500	500	4500
Integrated Data system												0
Data archive synthesis and support		600	600	600	600	600	600	600	600	600	600	6000
												0
Mission applications												0
measurement requirements analysis		300	300	300	300	300	300	300	300	300	300	3000
												0
Integrative Science and Data analysis												
Land component of coupled prognostic modeling efforts		500	500	500	500	500	500	500	500	500	500	5000
global land carbon cycle modeling		500	500	500	500	500	500	500	500	500	500	5000
land data assimilation		450	450	450	450	450	450	450	450	450	450	4500
Land science investigations		600	600	600	600	600	600	600	600	600	600	6000
	100	13150	17150	14850	9650	13550	8250	8050	8450	7450	7450	108100
Field Campaigns	100	500	6700	7900	3900	7800	2500	2500	2500	2500	2500	39400
Algo Dev/Cal Val	0	3700	1000	2500	1500	1500	1000	1000	1500	1000	1000	15700
In situ inst./Tech Dev	0	500	1000	1000	800	300	300	100	0	0	0	4000
Data Production & Synthesis	0	6100	6100	1100	1100	1600	2100	2100	2100	1600	1600	25500
Modeling/Data Assim/Sys Sim	0	1750	1750	1750	1750	1750	1750	1750	1750	1750	1750	17500
Science Investigations	0	600	600	600	600	600	600	600	600	600	600	6000

Figure 13. GCCP Ocean Activities

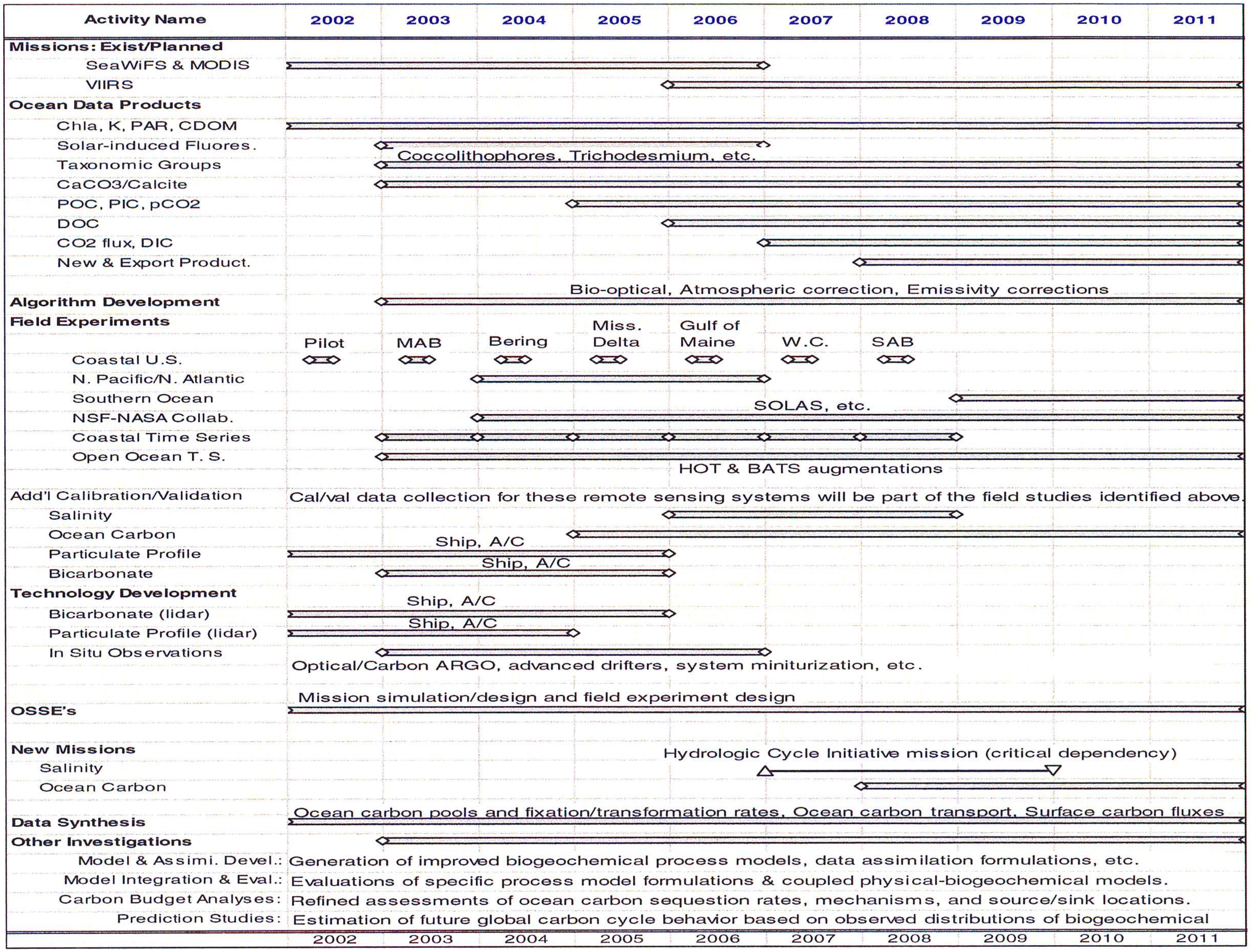
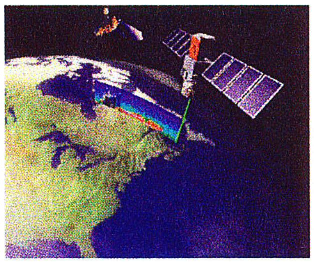


Figure 14. GCCP Ocean Budget (2001 K$)

Carbon Initiative Ocean Budget: Competed Ocean Components													
TOPIC	Subtopic	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	TOTAL
Algorithm Development													
(9 investigations(atmos & biogeo @ 150K/yr ea.)	In Situ Data Analysis		1350	1350	1350	1350	1350	1350	1350	1350	1350	1350	13500
Process/Algo. Dev./CalVal Experiments													
	Lab facilities & equip.	200	500	500	300	150	100	75	75	75	75	75	2125
(Biogeochem: 2 investigations @ 150K/yr ea.)	Lab studies	100	300	300	300	300	300	300	300	300	300	300	3100
(Gas exchange: 2 investigations @ 200/yr. ea)	Lab & field studies		400	400	400	400							1600
(Salinity, 1 investigation)	Spec. algo. field exp.		300	300	300								900
(**Coastal experiments:** 4 1-week seasonal	Ches. Bay/MAB		2580										2580
cruises with ship time @ $10K/day & 6	West Coast			2580									2580
investigations inc. PP, phyto. Physiology,	Mississippi Delta				2580								2580
organic chem, inorganic chem, air-sea flux,	Bering Sea					2580							2580
optics, @ 300K/yr ea. & A/C @ $500K/yr	South Atlantic Bight						2580						2580
per yr. ea.; coastal time series are simpler	Gulf of Maine							2580					2580
sets of frequent obs. to link major cruises;	Coastal Time Series		400	400	400	400	400	400	800	800	800	800	5600
Open ocean IWG studies: no ship time, 5 NASA	N. Atl./N. Pac. (IWG)			2000	2000	2000							6000
investigators @ $300/yr ea, (N.H.) + or $400K/yr	BATS augment.		200	200	200	200	200	200	200	200	200	200	2000
ea. (S.O.) + A/C (N.H.-$500K; S.O.-$700K)	HOT augment.		200	200	200	200	200	200	200	200	200	200	2000
	South. Ocean (IWG)								2700	2700	2700		8100
Other interagency collab., e.g., SOLAS,				1200	1200	1200	1200	1200	1200	1200	1200	1200	10800
6 investigators, 2 cruises/yr., 200K/yr ea.)													
Additional Calibration & Validation Experiments													
(over ESSP effort, 1 investigation)	Salinity (crit. depend.)					300	300	300					900
(covered under flight project budget)	Ocean Carbon												
(no shiptime)	Particulate Profile		200	200	200	200							800
Technology Development													
(covered under CCI Tech. Devel. Budget)	Bicarbonate lidar												
(covered under CCI Tech. Devel. Budget)	Particulate Profile lidar												
(covered under CCI Tech. Devel. Budget)	SuperAct.-Pas. sensor												
	In situ instruments		400	400	400	400							1600
Process Studies/Models, Data Synthesis & Analysis													
7-10 investigations @ 150k/yr ea.	C budget analyses		1050	1050	1050	1500	1500	1500	1500	1500	1500	1500	13650
	Data Production				500	500	500	500	500	500	500	500	4000
Coupled Models & Data Assimilation													
5-7 investigations @ 200K/yr ea., includes 3 staff	Model & assim. develop.		1450	1450	1450	1850	1850	1850	1850	1850	1850	1850	17300
for NSIPP @ 150K/yr.													
													109455
	TOTAL:	300	9330	12530	12830	13530	10480	10455	10675	10675	10675	7975	109455
DATE:	**06/04/01**												
Category Summary													
	Field Campaigns	0	3380	6580	6580	6580	4580	4580	5100	5100	5100	2400	
	Algo. Dev. & CalVal	300	3050	3050	2850	2700	2050	2025	1725	1725	1725	1725	
	In Situ Inst. Tech. Dev.	0	400	400	400	400	0	0	0	0	0	0	
	Data Production & Synthe	0	0	0	500	500	500	500	500	500	500	500	
	Modeling, Data Assim, Sy	0	1450	1450	1450	1850	1850	1850	1850	1850	1850	1850	
	Science Investigations	0	1050	1050	1050	1500	1500	1500	1500	1500	1500	1500	
													109455

Figure 15. CARBON CYCLE TECHNOLOGY/MISSION ROADMAP



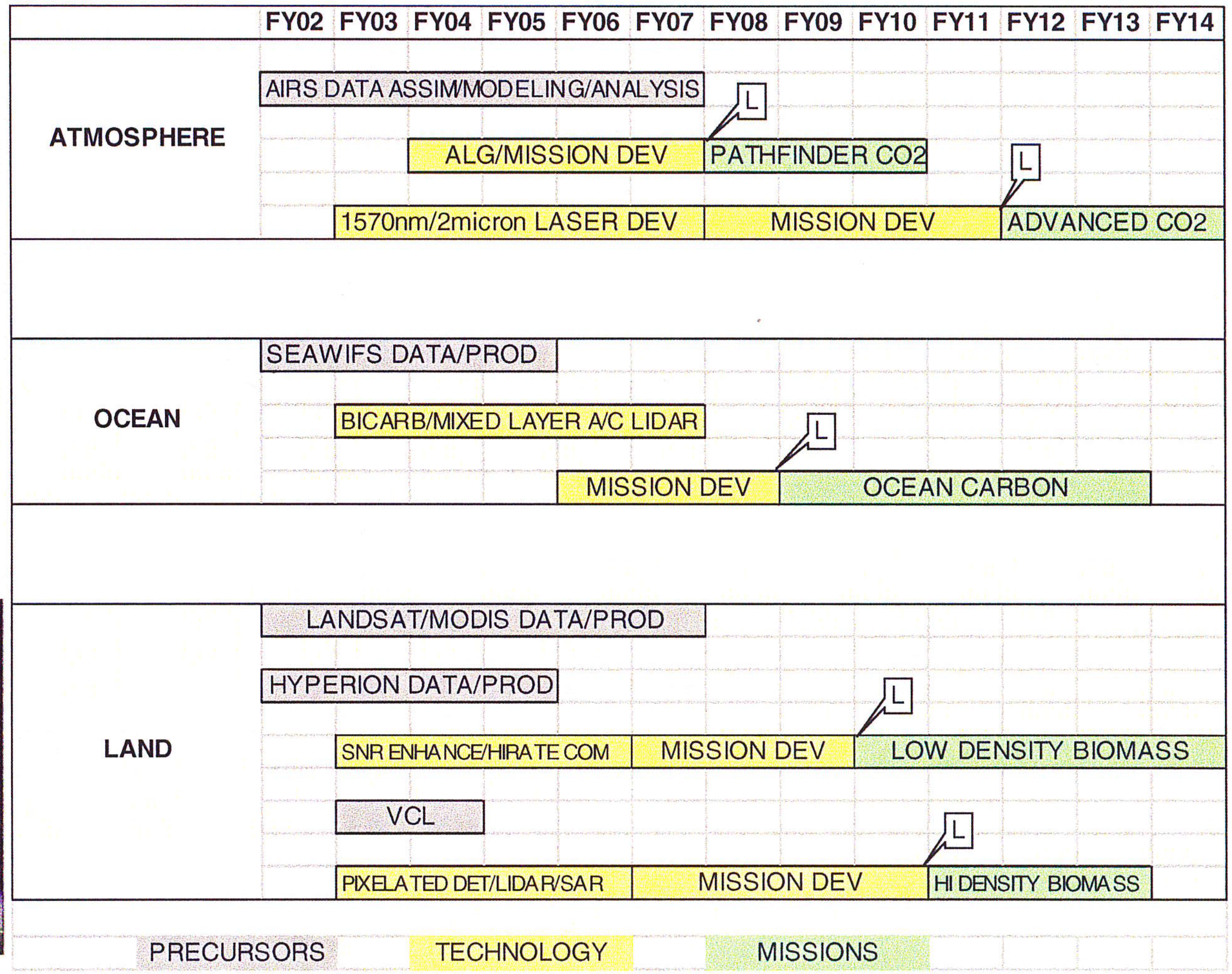
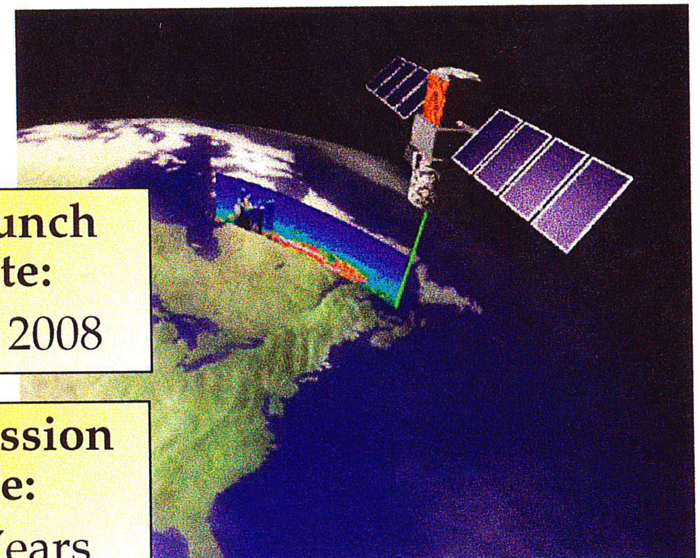


Figure 16. Laser Technology History

INSTRUMENT/MISSION	CONTACT	LAUNCH	ORBIT LifeTime (years)	Altitude (km)	Inclination (degrees)	Node (hour)	Type	Telescope (m)	Lasers (number)	Spot Size (m)	Energy (mJ)	Wavelength (nm)	PulseLength (nsec)
SLA-01	J. Garvin	1996	7 days	300	28.5		Nd:YAG			100		1064	10
SLA-02	J. Garvin	1997		300	57		Nd:YAG			30		1064	10
SLA-03				300	57		Nd:YAG			30		1064	10
MOLA													
LITE	D. Winker	1994	7 days	260	57		Nd:YAG	1	2	475		355/532/1064	
NEAR													
SPARCLE							Ho:Tm:YLF					2000	
ZEPHYR	R. Atlas							1			1000		
Clementine/SDIO													
MBLA/VCL	R. Dubayah	2003	1	400	67		Nd:YAG	0.9	3	25	15	1064	10
GLAS/ICESAT	R. Afzal	2001	3	600			Nd:YAG	0.8	3	70	35/75	532/1064	4
PICASSO-CENA		2004	2	705	SunSync	1330	Nd:YAG	1	2		100/110	532/1064	
Mercury Laser Altimeter	D. Smith	2004					Cr:Nd:YAG	0.25			50	1064	8
Europa Probe Laser Altimeter	D. Smith							0.15			5	1064	
Carbon Dioxide Lidar/GCCP	J. Abshire	2008	3	590	SunSync	0700/1900		1	10	100	6/2	760/1580	
Carbon Dioxide DIAL/GCCP	E. Browell			450			Ho:Tm:YLF	2.5			1000	2050	
Biomass Imaging Lidar/GCCP	R. Knox	2009	3	400	SunSync	1800	Nd:YAG/FO	1.5	3	75		1064	4 to 5
Biomass Imaging Lidar (DFO)	R. Knox	2009	3	400	SunSync	1800	FiberOptic	1.5	6	75		650/780	4 to 5
Mixed Layer Lidar	C. Koblinsky			8							50/100	532/1064	10

Figure 17. Pathfinder Atmospheric CO_2 Mission Profile

- **Description**: A small satellite mission that makes high-precision (1 to 2 ppmv) global measurements of atmospheric column CO_2 abundance
- **Instrument:** A passive spectrometer with a 10 km spatial resolution that provides high signal-to-noise ratio detection of atmospheric CO_2 and O_2 during the daytime portion of the orbit
- **Spacecraft:** A small, low-cost, three-axis stabilized, nadir pointing spacecraft from the RSDO catalog with a small propulsion system



Launch Date: FY 2008

Mission Life: 3 Years

Orbit: 500 to 700 km polar, sun-synchronous, with a morning crossing time

Space Access: Pegasus XL or equivalent class launch vehicle

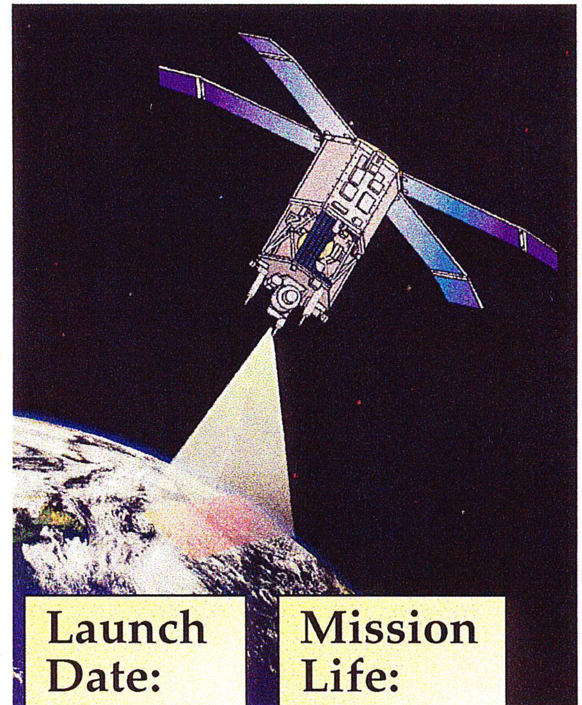
Key Technologies: S-Band LPT and other enhancing technologies at the subsystem or component level

Mission Options: Single dedicated mission as outlined above or as a complementary instrument on the Ocean Carbon mission

Figure 18. Ocean Carbon Mission Profile

- **Description:** A small satellite mission that makes those ocean color measurements critical to the determination of ocean biomass, primary productivity, and dissolved organic matter
- **Instrument:** A rotating, scanning telescope equipped with an on-board solar calibrator that makes irradiance measurements in 10 spectral bands from the ultraviolet to the near infrared
- **Spacecraft**: A small, low-cost, three-axis stabilized, nadir pointing spacecraft from the RSDO catalog with a propulsion system for orbit raising, maintenance, and maneuvers

Mission Options: A single instrument mission as outlined above or a combined mission that includes the Pathfinder Atmospheric CO2 measurement



Launch Date: FY 2009

Mission Life: 5 Years

Orbit: 705 km polar, sun-synchronous, with a 12:00 noon crossing time

Space Access: Pegasus XL or equivalent class launch vehicle

Figure 19. Low Density Biomass/Coastal Ocean Mission Profile

- **Description:** A satellite mission that provides a synoptic view of the Earth's ecosystems, their spatial distribution, and temporal dynamics with global measurements of land cover, land cover change, and ocean surface chlorophyll
- **Instrument:** A hyperspectral imager providing high signal-to-noise ratios and covering a frequency range from 450 to 2350 nm with a SWIR bandwidth of 10 nm and a VNIR bandwidth of 5 nm
- **Spacecraft:** A low-cost, three-axis stabilized, nadir pointing spacecraft from the RSDO catalog with a propulsion system sized to allow formation flying with other land imaging platforms

Key Technologies: Large area focal plane arrays, large capacity on-board recorders, and high rate downlink systems for improved mission performance

Launch Date: FY 2010

Mission Life: 5 Years

Orbit: 705 km circular sun-synchronous with a 10:30 a.m. descending node

Space Access: Taurus or equivalent class launch vehicle

Figure 20. High Density Biomass Mission Profile

- **Description:** A satellite mission that provides improved regional and global estimates of vegetation biomass and carbon stocks, studies the response of terrestrial ecosystems to major disturbances, and measures the rate of recovery
- **Instruments:** A P-band SAR operating at 0.44 GHz and a multi-track, 1.064 micron, imaging laser altimeter with a capability of resolving 0.5 m differences in vegetation height
- **Spacecraft:** A three-axis stabilized, nadir pointing spacecraft from the RSDO catalog modified to accommodate a large propulsion system and an X-band phased array

Launch Date: FY 2011

Mission Life: 3 Years

Key Technologies: High resolution P-band polarimetric SAR, pixelated detectors, a high-accuracy attitude & position knowledge package, laser diode efficiency & lifetime improvements, & an S-band low power transceiver

Orbit: 400 km polar sun-synchronous with a 6:00 p.m. ascending node

Space Access: Delta II or equivalent class launch vehicle

Figure 21. Advanced Atmospheric CO_2 Mission Profile

- **Description:** A satellite mission that measures the global concentration of carbon dioxide and oxygen in the lower troposphere
- **Instruments:** A pulsed, dual frequency, tunable laser sounder operating in the 1570 nm band for carbon dioxide detection and in the 770 nm band for oxygen detection; Options include a 2 micron coherent laser absorption spectrometer or a differential absorption lidar for CO_2 vertical profiling
- **Spacecraft:** A low-cost, three-axis stabilized, nadir pointing spacecraft from the RSDO catalog with a propulsion system and appropriate subsystem modifications

Launch Date: FY 2012

Mission Life: 3 Years

Orbit: 590 km circular sun-synchronous with a 7:00 a.m. or 7:00 p.m. ascending node

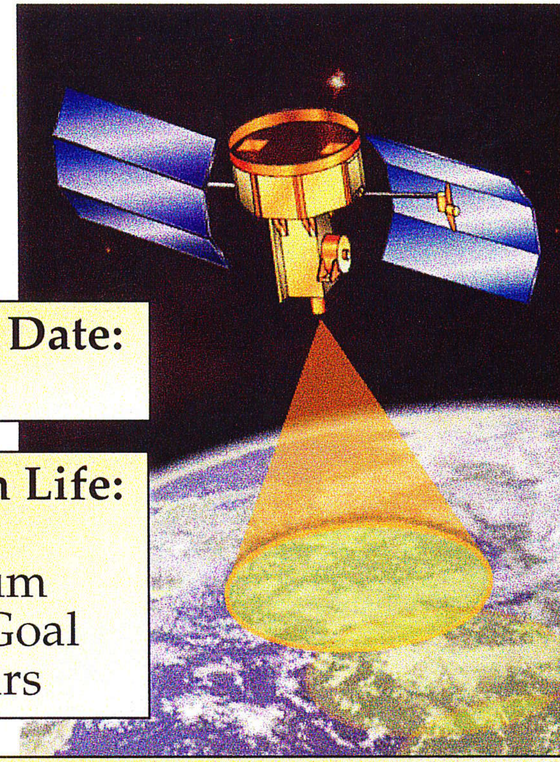
Space Access: Delta 2320-10 or equivalent class launch vehicle

Key Technologies: 1570 nm and 2 micron lidar sensor technology development, S-band low power transceiver

Figure 22. Aerosols Mission Profile

- **Description:** A small satellite mission that measures the spatial distribution and seasonal variability of atmospheric aerosols on a global scale and determines their effect on the Earth's energy balance
- **Instrument:** Multi-angle, multi-spectral, scanning photopolarimeter with an on-board calibrator operating at 100% duty cycle during the daytime portion of the chosen orbit
- **Spacecraft:** A small, low-cost, three-axis stabilized, nadir pointing spacecraft from the RSDO catalog with no propulsion system

Mission Options: Single dedicated mission as outlined above, dual spacecraft in LEO and sun-synchronous orbits, or flight of instrument as a payload of opportunity on other spacecraft



Launch Date: FY 2008

Mission Life: 2 Years Minimum with a Goal of 5 Years

Orbit: 550 km circular with an inclination of 60 degrees

Space Access: Pegasus XL or equivalent class launch vehicle

Key Technologies: S-band LPT & other enhancing technologies at the subsystem or component level

Figure 23. BASELINE MEASUREMENT SET

Mission	Launch (FY)	Lifetime (Years)	LCC (2001M$)
Pathfinder CO_2	**2008**	**3**	**$138**
Ocean Carbon	**2009**	**5**	**$184**
Low Density Biomass/Coastal Ocean	**2010**	**5**	**$324**
High Density Biomass	**2011**	**3**	**$386**
Advanced CO_2	**2012**	**3**	**$312**
Technology Development			**$110**

Assumes VCL launch & no ESSP CO_2 selection

Figure 24. Cost Spreading as a Function of Launch Year

ELEMENT	SPREADING AS A FUNCTION OF LAUNCH YEAR								
	L-7	L-6	L-5	L-4	L-3	L-2	L-1	L	L+1
TECHNOLOGY DEVELOPMENT	34%	45%	21%						
INSTRUMENT				12%	35%	34%	19%		
SPACECRAFT					12%	35%	34%	19%	
LAUNCH VEHICLE						23%	39%	33%	5%
CONTINGENCY				5%	14%	22%	27%	21%	11%

Figure 25. GCCP Pathfinder CO_2 Mission Cost Profile

ELEMENTS OF COST	FY02	FY03	FY04	FY05	FY06	FY07	FY08 Launch	FY09	FY10	FY11	Total
Preformulation	0.2	0.2									0.4
Formulation		0.7	1.8								2.5
Project Management			0.3	1	1	1	0.5	0.2			4
Instrument Design/Development			2	7	7	4					20
Spacecraft Design/Development				4	12	12					28
Mission Systems Integration/Test							6				6
Launch Vehicle/Services					6	11	9	1			27
Ground/Data System Accommodations							1	2	2	1	6
Mission Operations/Data Analysis					1	6	5	2	2	1	17
Post-Launch Calibration/Validation								1	1	1	3
Contingency	0	0	1	3	5	7	5	3	0	0	24
TOTAL	0.2	0.9	5	15	32	41	27	9	5	3	138

Figure 26. GCCP Ocean Carbon Mission Cost Profile

ELEMENTS OF COST	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	FY13	FY14	Total
								Launch						
Preformulation		0.2	0.2											0.4
Formulation			0.7	1.8										2.5
Project Management				0.3	1	1	1	0.5	0.2					4
Instrument Design/Development				5	16	15	9							45
Spacecraft Design/Development					4	13	12							29
Mission Systems Integration/Test								7						7
Launch Vehicle/Services						6	11	9	1					27
Ground/Data System Accommodations								1	2	2	2	2	1	10
Mission Operations/Data Analysis						1	6	5	3	2	2	2	1	22
Post-Launch Calibration/Validation									1	1	1	1	1	5
Contingency	0	0	0	2	4	7	9	7	3	0	0	0	0	32
TOTAL	0	0.2	0.9	9	25	43	48	30	10	5	5	5	3	184

Figure 27. GCCP Low Density Biomass Mission Cost Profile

ELEMENTS OF COST	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10 Launch	FY11	FY12	FY13	FY14	FY15	Total
Preformulation		0.3	0.3											0.6
Formulation			1.5	2										3.5
Project Management				0.5	1	1.5	1.5	1	0.5					6
Instrument Design/Development				13	37	36	20							106
Spacecraft Design/Development					5	16	15							36
Mission Systems Integration/Test								9						9
Launch Vehicle/Services						11	18	15	2					46
Ground/Data System Accommodations							1	3	5	5	5	5	1	25
Mission Operations/Data Analysis						2	6	5	5	3	3	3	1	28
Post-Launch Calibration/Validation									1	1	1	1	1	5
Contingency	0	0	0	3	8	13	16	13	6	0	0	0	0	59
TOTAL	0	0.3	1.8	18	51	80	77	46	20	9	9	9	3	324

Figure 28. GCCP High Density Biomass Mission Cost Profile

ELEMENTS OF COST	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11 Launch	FY12	FY13	FY14	Total
Preformulation				0.3	0.3									0.6
Formulation					2	2.5								4.5
Project Management						0.5	1.5	2	2	1.5	0.5			8
Instrument Design/Development						16	48	47	26					137
Spacecraft Design/Development							7	19	19					45
Mission Systems Integration/Test										10				10
Launch Vehicle/Services								13	23	19	3			58
Ground/Data System Accommodations									1	6	6	5	2	20
Mission Operations/Data Analysis								3	5	6	5	4	2	25
Post-Launch Calibration/Validation											1	1	1	3
Contingency	0	0	0	0	0	4	10	17	20	16	8	0	0	75
TOTAL	0	0	0	0.3	2	23	67	101	96	58	24	10	5	386

Figure 29. GCCP Advanced CO_2 Mission Cost Profile

ELEMENTS OF COST	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	FY13	FY14	FY15	Total
										Launch				
Preformulation				0.3	0.3									0.6
Formulation					1.5	2								3.5
Project Management						0.5	1	1.5	1.5	1	0.5			6
Instrument Design/Development						14	40	38	21					113
Spacecraft Design/Development							5	15	14					34
Mission Systems Integration/Test										8				8
Launch Vehicle/Services								13	23	19	3			58
Ground/Data System Accommodations										0.5	1	1	1	3.5
Mission Operations/Data Analysis								1	4	6	4	2	1	18
Post-Launch Calibration/Validation											1	1	1	3
Contingency	0	0	0	0	0	3	9	14	18	13	7	0	0	64
TOTAL	0	0	0	0.3	1.8	20	55	82	82	47	17	4	3	312

Figure 30. GCCP Aerosols Mission Cost Profile

ELEMENTS OF COST	FY02	FY03	FY04	FY05	FY06	FY07	FY08 Launch	FY09	FY10	FY11	Total
Preformulation	0.2	0.2									0.4
Formulation		0.7	1.8								2.5
Project Management			0.3	1	1	1	0.5	0.2			4
Instrument Design/Development			2	6	5	3					16
Spacecraft Design/Development				4	12	12					28
Mission Systems Integration/Test							5				5
Launch Vehicle/Services					6	11	9	1			27
Ground/Data System Accommodations							0.5	1.5	1	1	4
Mission Operations/Data Analysis					1	4	6	4	2	1	18
Post-Launch Calibration/Validation								1	1	1	3
Contingency	0	0	1	3	5	6	5	3	0	0	23
TOTAL	0.2	0.9	5	14	30	37	26	11	4	3	131

Figure 31. GCCP Mission/Technology Costs (2001 M$, FY02-FY15)

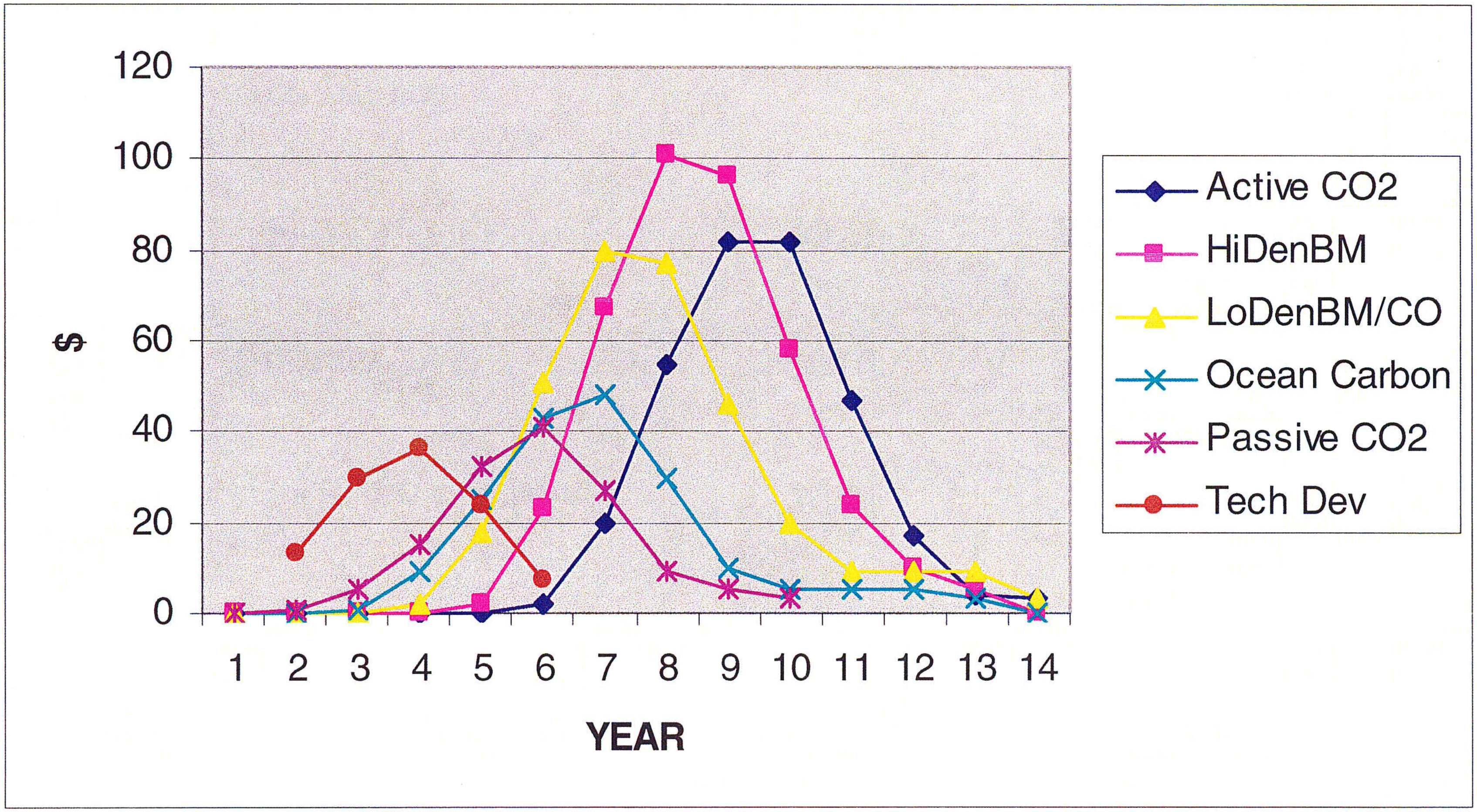


Figure 32. REDUCED MEASUREMENT SET
Option 1

Mission	Launch (FY)	Lifetime (Years)	LCC (2001M$)
Pathfinder CO_2 / Ocean Carbon	2008	3	$244
High Density Biomass	2010	3	$386
Advanced Atmospheric CO_2	2012	3	$312
Technology Development			$ 98

Assumes no VCL launch and no ESSP CO_2 selection.

Figure 33. REDUCED MEASUREMENT SET
Option 2

Mission	Launch (FY)	Lifetime (Years)	LCC (2001M$)
Pathfinder CO_2/ Ocean Carbon	**2008**	**3**	**$244**
Advanced Atmospheric CO_2	**2010**	**3**	**$312**
High Density Biomass	**2012**	**3**	**$386**
Technology Development			**$ 98**

Assumes VCL launch and no ESSP CO_2 selection.

Figure 34. REDUCED MEASUREMENT SET
Option 3

Mission	Launch (FY)	Lifetime (Years)	LCC (2001M$)
Ocean Carbon	2008	5	$184
High Density Biomass	2012	3	$386
Advanced Atmospheric CO_2	2010	3	$312
Technology Development			$ 98

Assumes no VCL launch and ESSP CO_2 selection.

Figure 35. REDUCED MEASUREMENT SET
Option 4

Mission	Launch (FY)	Lifetime (Years)	LCC (2001M$)
Ocean Carbon	2008	5	$184
Advanced Atmospheric CO_2	2010	3	$312
High Density Biomass	2012	3	$386
Technology Development			$ 98

Assumes VCL launch and ESSP CO_2 selection.

Figure 36. AIRCRAFT DEMONSTRATIONS

ATMOSPHERE

- **Carbon Dioxide Column Measurement**
- **Carbon Dioxide Profiling**

OCEAN

- **Ocean Particulate Lidar**
- **Ocean Bicarbonate Lidar**

LAND

- **Single Frequency Biomass Imaging**
- **Dual Frequency Biomass Imaging**
- **Hyperspectral Imaging**
- **Synthetic Aperture Radar**

Figure 37. GCCP CO_2 COLUMN MEASUREMENT AIRCRAFT MISSION COST SUMMARY (2001 K$)

ELEMENTS OF COST	COST	SOURCE
Project Management	80	% TOTAL
Instrument Design/Development/Test	590	PI
Aircraft Interface Accommodations	100	PI
Ground Support Equipment	50	INTERNAL ESTIMATE
Flight Operations Services	297	AIRCRAFT PROJECT
Flight Data Analysis	300	PI
Contingency	213	% TOTAL
TOTAL	1630	

Figure 38. GCCP CO_2 PROFILING AIRCRAFT MISSION COST SUMMARY (2001 K$)

ELEMENTS OF COST	COST	SOURCE
Project Management	100	% TOTAL
Instrument Design/Development/Test	820	PI
Aircraft Interface Accommodations	100	PI
Ground Support Equipment	50	INTERNAL ESTIMATE
Flight Operations Services	636	AIRCRAFT PROJECT
Flight Data Analysis	200	PI
Contingency	286	% TOTAL
TOTAL	2192	

Figure 39. GCCP OCEAN PARTICULATE LIDAR AIRCRAFT MISSION COST SUMMARY (2001 K$)

ELEMENTS OF COST	COST	SOURCE
Project Management	150	% TOTAL
Instrument Design/Development/Test	570	PI
Aircraft Interface Accommodations	100	PI
Ground Support Equipment	50	INTERNAL ESTIMATE
Flight Operations Services	1599	AIRCRAFT PROJECT
Flight Data Analysis	500	PI
Contingency	445	% TOTAL
TOTAL	3414	

Figure 40. GCCP OCEAN BICARBONATE LIDAR AIRCRAFT MISSION COST SUMMARY (2001 K$)

ELEMENTS OF COST	COST	SOURCE
Project Management	5	% TOTAL
Instrument Design/Development/Test	100	PI
Aircraft Interface Accommodations	0	
Ground Support Equipment	0	
Flight Operations Services	514	PI
Flight Data Analysis	100	PI
Contingency	108	% TOTAL
TOTAL	827	

Figure 41. GCCP SINGLE FREQUENCY BIOMASS IMAGING AIRCRAFT MISSION COST SUMMARY (2001 K$)

ELEMENTS OF COST	COST	SOURCE
Project Management	200	% TOTAL
Instrument Design/Development/Test	660	PI
Aircraft Interface Accommodations	200	PI
Ground Support Equipment	50	INTERNAL ESTIMATE
Flight Operations Services	3101	AIRCRAFT PROJECT
Flight Data Analysis	300	PI
Contingency	677	% TOTAL
TOTAL	5188	

Figure 42. GCCP DUAL FREQUENCY BIOMASS IMAGING AIRCRAFT MISSION COST SUMMARY (2001 K$)

ELEMENTS OF COST	COST	SOURCE
Project Management	200	% TOTAL
Instrument Design/Development/Test	860	PI
Aircraft Interface Accommodations	200	PI
Ground Support Equipment	50	INTERNAL ESTIMATE
Flight Operations Services	2651	AIRCRAFT PROJECT
Flight Data Analysis	300	PI
Contingency	639	% TOTAL
TOTAL	4900	

Figure 43. GCCP HYPERSPECTRAL IMAGING AIRCRAFT MISSION COST SUMMARY (2001 K$)

ELEMENTS OF COST	COST	SOURCE
Project Management	0	
Instrument Design/Development/Test	0	
Aircraft Interface Accommodations	0	
Ground Support Equipment	0	
Flight Operations Services	940	INTERNAL ESTIMATE
Flight Data Analysis	900	INTERNAL ESTIMATE
Contingency	276	% TOTAL
TOTAL	2116	

Figure 44. GCCP RADAR AIRCRAFT MISSION COST SUMMARY (2001 K$)

ELEMENTS OF COST	COST	SOURCE
Project Management	0	
Instrument Design/Development/Test	0	
Aircraft Interface Accommodations	0	
Ground Support Equipment	0	
Flight Operations Services	472	INTERNAL ESTIMATE
Flight Data Analysis	600	INTERNAL ESTIMATE
Contingency	161	% TOTAL
TOTAL	1233	

Figure 45. GCCP SUMMARY OF AIRCRAFT MISSIONS COSTS (2001 K$)

AIRCRAFT MISSION	COST OF INSTRUMENT	COST OF MISSION	AIRCRAFT	FLIGHT HOURS
Carbon Dioxide Column	590	1630	LearJet	80
Carbon Dioxide Profiling	820	2192	P3b	50
Ocean Particulate LIDAR	570	3414	P3b	40
Ocean Bicarbonate LIDAR*	100	827	P3b	30
Single Frequency Biomass LIDAR	660	5188	P3b	60
Dual Frequency Biomass LIDAR	860	4900	P3b	60
Hyperspectral*	0	2116	Twin Otter	30
Radar (P-Band SAR)*	0	1233	DC-8	30

* - ACCOMMODATION ONLY

Figure 46. TECHNOLOGY READINESS LEVELS (TRLs)

TRL 1: **Basic principles observed and reported**

TRL 2: **Technology concept and/or application formulated**

TRL 3: **Analytical and experimental function or proof-of-concept**

TRL 4: **Component and/or breadboard validation in laboratory environment**

TRL 5: **Component and/or breadboard validation in relevant environment**

TRL 6: **Subsystem/system model or prototype demonstration in a relevant environment**

TRL 7: **System prototype demonstration in a space environment**

TRL 8: **Actual system completed and flight qualified through test**

TRL 9: **Actual system flight proven through successful mission operations**

Figure 47. Biomass Imaging Lidar Technology Readiness

Element/TRL	1	2	3	4	5	6	7	8	9	Remarks
Component										
Telescope						X				Vendor Quote Of $3.5M
Aft Optics					X					VCL Heritage
Optical Bench						X				VCL Heritage
Laser Transmitters				X						1 kHz Measurement Rate
Pixelated Detectors				X						Several Options To Consider
Data Electronics					X					Laser Program Heritage
A/D Converter		X								Digitization Rate Issue
Processor						X				Cross-Cutting Technology
Power Supplies						X				Laser Program Heritage
Thermal Controls							X			Laser Program Heritage
Heat Pipes							X			Minor Component Modifcation
Phase Change Modules							X			Minor Component Modifcation
Radiators							X			Minor Component Modification
Cable Harness							X			Minor Component Modification
Isolation/Support Fixture							X			GLAS Heritage
Subsystem/System										
Integration & Test						X				Procedures Derived From GLAS And VCL
Instrument		2.5								Packaging/Qualification Effort

Note: TRL Of 6 Required For Start Of Implementation Phase .

Figure 48. Dual Frequency Biomass Imaging Lidar Technology Readiness

Element/TRL	1	2	3	4	5	6	7	8	9	Remarks
Component										
Telescope						X				Vendor Quote Of $3.5M
Aft Optics				X						Chromatic Split Required
Optical Bench						X				VCL Heritage
Laser Transmitters		X								Dual Frequency Configuration
Pixelated Detectors				X						Several Options To Consider
Data Electronics					X					Laser Program Heritage
A/D Converter		X								Digitization Rate Issue
Processor						X				Cross-Cutting Technology
Power Supplies						X				Laser Program Heritage
Thermal Controls							X			Laser Program Heritage
Heat Pipes							X			Minor Component Modifcation
Phase Change Modules							X			Minor Component Modifcation
Radiators							X			Minor Component Modification
Cable Harness							X			Minor Component Modification
Isolation/Support Fixture							X			GLAS Heritage
Subsystem/System										
Integration & Test				X						Unqualified Fiber Optic Components New Procedures Required
Instrument		X								Packaging/Qualification Effort Airborne Proof Of Concept Needed

Note: TRL Of 6 Required For Start Of Implementation Phase

Figure 49. CO_2 Laser Sounder Technology Readiness

Element/TRL	1	2	3	4	5	6	7	8	9	Remarks
Component										
Telescope						X				GLAS Heritage
Relay Optics						X				GLAS Heritage
Optical Bench						X				GLAS Heritage
1570 nm (CO2) Lasers				X						ATIP Status
770 nm (O2) Lasers			X							
CO2 Reference Cells			X							Needs Further Assessment
O2 Reference Cells			X							Needs Further Assessment
Beam Switching Mech						X				
Transmit Turning Optics						X				GLAS Heritage
CO2 Channel Detectors										
IR Photomultiplier Tubes			X							
02 Channel Detectors										
Single Photon Counting Modules						X				GLAS Heritage
Instrument Electronics							X			Laser Program Heritage
Flight Computer							X			
Power Supplies							X			Laser Program Heritage
Thermal Controls						X				Laser Program Heritage
Loop Heat Pipes							X			Minor Component Modifcation
Thermoelectric Coolers							X			Minor Component Modifcation
Radiators							X			Minor Component Modification
Cable Harness							X			Minor Component Modification
Isolation/Support Fixture							X			GLAS Heritage
Subsystem/System										
Integration & Test				X						
Flight Algorithms/Software				X						
Instrument			X							Packaging/Qualification Effort

Note: TRL Of 6 Required For Start Of Implementation Phase

Figure 50. Differential Absorption Lidar Technology Readiness

Element/TRL	1	2	3	4	5	6	7	8	9	Remarks
Component										
Deployable telescope										
Design			X							
Prototype demonstration	X									
Component testing		X								
Aft Optics										
Filter	X									
Design				X						
Component testing		X								
Laser Transmitters										
Conductively cooled diodes			X							
Conductively cooled laser	X									
Laser diode lifetime			X							
Double pulse laser			X							
Laser transmitter thermal			X							
New laser materials	X									
Damage resistant optics	X									
Double pulse injection seed		X								
Laser packaging			X							
Detector			X							
Signal processing	X									
Integration & Test	X									

Figure 51. TECHNOLOGY DRIVERS

- **Carbon Dioxide Lasers (1570 nm)**
- **Oxygen Lasers (770 nm)**
- **Reference Cells**
- **2 micron DIAL System Elements**
- **Infrared Photomultiplier Tubes**
- **Laser Transmitters (green and red edge) for Biomass Imaging**
- **Pixelated Detectors**
- **High Digitization Rate A/D Converters**
- **High Signal To Noise Ratio Detector Systems**
- **Ka-Band Space To Ground Systems**
- **Packaging/Qualification Of Commercial Laser Components**

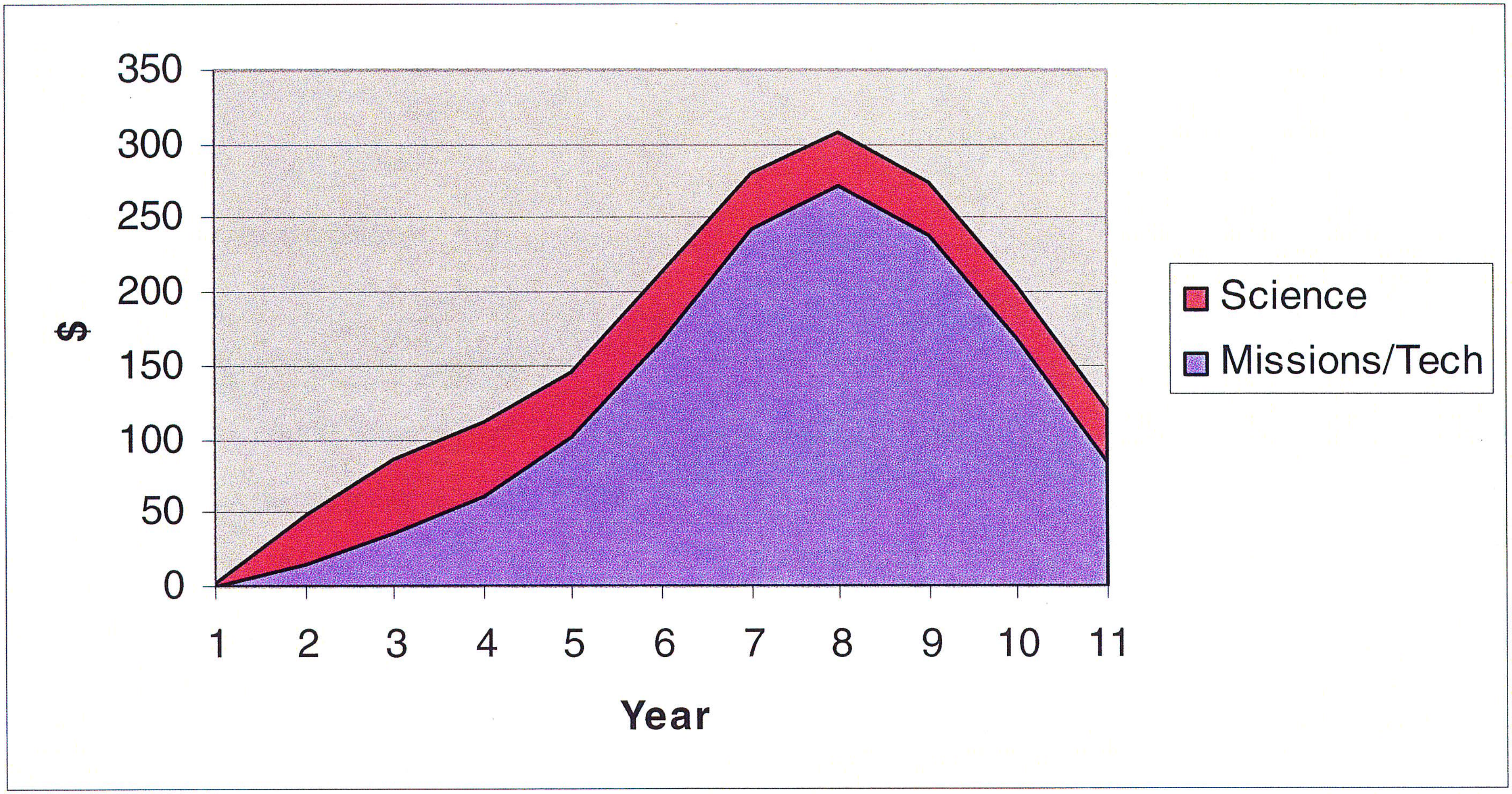
Figure 52. GCCP TECHNOLOGY DEVELOPMENT COSTS

	Funding (2001 M$, FY03-FY07)
• Mission Common Technology	
– Laser/Lidar Common	**15**
– High Rate Data/Communication	**6**
– On-Board Data Processing	**4**
– Precision Geolocation	**3**
• Mission Specific Technology	
– Pathfinder Atmospheric CO_2	**None Required**
– Ocean Carbon	**None Required**
– Low Density Biomass/Coastal Ocean	**6**
– High Density Biomass/Lidar	**36**
– High Density Biomass/Radar	**7**
– Advanced Atmospheric CO_2	**33**
• TOTAL	110

Figure 53. GCCP Technology Development Cost Profile

ELEMENTS OF COST	FY02	FY03	FY04	FY05	FY06	FY07	
MISSION SPECIFIC							
Pathfinder Atmospheric CO2		None Required					0
Ocean Carbon		None Required					0
Low Density Biomass/Coastal Ocean		1	3	2			6
High Density Biomass/Lidar		4	13	12	7		36
High Density Biomass/Radar		1	2.5	2.5	1		7
Advanced Atmospheric CO2		3	5	10	10	5	33
MISSION COMMON							
Laser/Lidar Common		2	3	5	3	2	15
High Rate Data/Communications		1	2	2	1		6
On-Board Data Processing		1	1	1	1		4
Precision Geolocation		0.5	1	1	0.5		3
TOTAL		13	30	36	24	7	110

Figure 54. GCCP Science/Technology/ Mission Cost Profile (2001 M$, FY02-FY12)



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This volume presents the costs estimated for the science and engineering implementation of the Recommended NASA Carbon Cycle Research, as of August 31, 2001. The research activities have since been refined and folded into a broader program plan for contributing to the President's Climate Change Research Initiative. A brief introduction describes the process used to develop the measurements, activities, and missions from science goals in preparation for costing. Program content is described in much greater detail in a NASA Technical Memorandum entitled Science and Observation Recommendations for Future NASA Carbon Cycle Research.

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