[redacted]

IDP - 098

SMALL SATELLITES

How might DoD- and DOE-originated instrument concepts be used in the Global Change Research Program?

C. Max
J. Vesecky

JSR-91-330-10

August 3, 1991

JASON
The MITRE Corporation
7525 Colshire Drive
McLean, VA 22102-3481
(703) 883-6997

Contents

1 INTRODUCTION

Among the suggestions for small satellite missions in support of the Global Change Research Program is a set of very small, very light satellite instruments, suggested by members of the Brilliant Pebbles program. These have been dubbed "microsats" and "lightsats", because they are proposed to have weights ranging from one twentieth to one hundredth of the weights of EOS instruments which perform roughly analogous functions. In principle the extremely small size of these instruments could permit deployment of quite a large constellation of "microsats", if the small weights are reflected in similarly small costs for the systems.

In a less extreme version, participants from DARPA and from the DOE laboratories have put forward proposals for satellite instruments that are somewhat larger and heavier, but still well below the weights of instruments contemplated for the EOS platforms.

In this section we will comment on what roles make sense for such instruments, within the context of the Global Change Research Program.

We suggest that proposals for small satellites and microsats be approached following the same guiding principle:

1. **Decide on several specific candidate missions for small satellites, including possible microsats. Then ask, what size satellite and how large a constellation are needed to do the job of each of these missions.**

To us, a focus on candidate science missions makes much more sense than the approach used in several presentations we heard, which looked one by one at EOS instruments, and then tried to duplicate their individual functions with "microsat" or "lightsat" technology. An integral approach based on the geophysical knowledge needed to understand a specific global change issue seems to us to be more fruitful. Below we will suggest several such "issue specific" science missions which seem to us to be useful candidates for further development.

In addition, there are a few specific EOS instruments which are in some sense in difficulty, either because the desired technology is not yet mature or because of various technical problems. We suggest that

1. **The community should look carefully at the few EOS instruments that are in some sense in trouble, and determine if and how their science missions might be usefully accomplished by a combination of much smaller satellites.**

In the text to follow we will suggest specific science missions that might benefit from going through this exercise. We point out that the process of evaluating whether the missions can be fruitfully accomplished by smaller instruments may well have benefical effects for the EOS platforms themselves, since the smaller instruments could either be flown on separate small satellites or together on the larger EOS satellites. The choice between these two options should be made based on the ability to accomplish the specific science missions in a timely, effective, and cost-efficient way.

2 CANDIDATE SCIENCE MISSIONS FOR SMALL SATELLITES

One class of science mission that is well suited to small satellites is measurements for which several satellite platforms are needed, in order to accumulate acceptable statistics on quantities subject to large temporal variations. Missions to monitor the earth's radiation budget and missions to measure global rainfall are in this category. Specifics of these two missions are discussed elsewhere in this report. Here we give only a brief overview.

1. Earth Radiation Budget Mission.

Global radiation budget measurements require at least three satellites, if adequate statistics on monthly regional means are to be obtained. The instrument package can be designed to weigh one to two hundred kilograms or less, thus qualifying for the "small satellite" designation. Because one needs to measure monthly averages to 1% accuracy in order to detect the expected signal from increased atmospheric CO_2 concentrations, radiation budget satellites require great attention to calibration and stability issues. For this reason, we recommend for the near term that ERBE or CERES type instruments be considered, due to their well-established heritage and well-understood calibration.

These radiation measuring instruments must be accompanied by an instrument to classify scene types using some sort of cloud measurements. There seems to us to be room for considerable innovation in the design of this second instrument. The MODIS experiment on EOS is designed to perform many more functions than the simple cloud imager needed for only the radiation budget function, and MODIS is consequently much heavier than such an instrument needs to be.

Along with the radiation measurements and the cloud imager, there is the possiblity of including other functions on the radiation budget satellites, although at the cost of increased weight and power requirements. Hansen has proposed (Hansen et al. 1991) a limb-scanning spectrometer (SAGE III), a solar photopolarimeter (EOSP) for aerosol and cloud characteristics, and a thermal Michaelson interferometer for cloud properties. (In Hansen's case this last instrument plays the role of the cloud imager mentioned above.)

Our own preference would be to put the limb measurements on a separate small satellite mission (described below), since they do not have the same simultaneity and congruence requirements that the nadir-looking instruments have. Attractive options for instruments to accompany the radiation budget experiment include a capability for determining cloud-top height (for example via stereo images or a small cloud-top LIDAR), or an imaging spectrometer such as the MPIR instrument proposed by Vitko et al (1991).

The decision concerning which accompanying instruments make sense should be made based on flying the minimum number (and weight) of instruments that can do a good job on the specific science mission. This decision is closely coupled (via the total mission cost) with the decision on how many satellites must fly simultaneously in order to obtain the desirable level of statistical accuracy. Sampling analyses are absolutely critical to the issue of determining how much orbital coverage is needed. The sampling analyses are not merely straightforward applications of conventional statistical methods; they must include an analysis of the actual algorithms used to unfold the net radiation budget from the raw data, using statistical models of the bi-directional radiance function and taking into account the determination of the scene type.

2) Limb-Scanning Mission: Stratosphere, Mesosphere, and Upper Troposphere.

This mission would include several instruments that make limb-scanning measurements of the stratosphere, mesosphere, and upper troposphere. Candidates are SAGE type grating spectrometers for temperature profiles, aerosols, and measurements of molecules such as O_3, H_2O, NO_2, and NO_3 down to the cloud tops, a lighter equivalent of the HIRDLS scanning radiometer, a lighter equivalent of the SWIRLS stratospheric wind sounder, or (if technically possible) a lightweight microwave limb sounder.

3) Global Precipitation Mission.

Knowledge of global precipitation trends is critical to assessing changes in the hydrological cycle. Yet global rainfall is not known at present to within a factor of two. Satellite-based rain radars and passive microwave sounders will be tested on an aircraft platform (ARMAR) beginning in late 1991, on the TRMM satellite mission to be launched in 1997, and later on the two JEOS platforms. These new instruments are designed to reduce the variances of the rain-rate measurements from the present 30%-50% to perhaps the 10% level. Together with the increased geographical coverage possible from a modest constellation of satellites, these new instruments offer the possibility for the first time of doing meaningful global monitoring of rainfall and precipitation patterns.

Rainfall is known to be very variable both spatially and temporally. In the spatial dimension, even ground-based rain-gauge measurements do not converge particularly well, and there have been suggestions that spatial rainfall patterns are fractal. In the temporal dimension, tropical rainfall statistics have variances that are just as large as the mean. As a result, it will be difficult for one satellite to accumulate enough independent data points to lower the uncertainty of even monthly averaged regional rainfall rates. Sampling analyses based on the TRMM data will be needed in order to decide on how large a constellation is required to do a meaningful job of monitoring changes in the global rainfall and precipitation rates.

3 SMALL SATELLITE INSTRUMENTS TO ADDRESS PROBLEMS FACING PRESENT EOS-CLASS EXPERIMENTS

A few of the instruments proposed for EOS A and B are currently facing technical problems of various kinds. In the process of addressing these problems, it seems to us to be fruitful to address whether there are advantages to be gained from splitting up the scientific functions of these large instruments into two or more smaller experiments. The resulting subdivided instrumentation could then either be flown together on an EOS platform, or flown separately on smaller satellites. A potential advantage of the latter could be that time-urgent segments of the mission would have the possibility of being flown sooner.

We discuss below some of the EOS instruments which have been mentionned to us as having various implementation problems at present. We recognize that many of these implementation problems are only temporary, and we do not mean to imply by including an EOS instrument on our list that its status is necessarily in doubt. Rather, we present these options as examples of a class of experiment where innovative technology from the defense community may be of help in the future in broadening the design options for global change missions.

1. Solid-state Lasers for LIDARS and Laser Rangers.

The Geosciences Laser Ranging System (GLRS) proposed for EOS B consists of a solid-state Nd:YAG laser running at 40 pulses per second, which is doubled and tripled in frequency. As designed, the laser's average output power is between 10 and 15 watts. The GLRS has several distinct applications: laser ranging for geodynamical measurements of crustal motions, ice-sheet altimetry and motion, along-track cloud and aerosol distributions and vertical profiles, and cloud and aerosol backscatter cross sections. The current design calls for one laser to accomplish all of these applications.

As specified, the laser hardware requirements for GLRS are quite challenging. However, laser requirements for individual LIDARs to accomplish the mission goals one by one are in many instances less stressing. For example, a cloud-height LIDAR can be much less powerful than a laser-ranging laser. Similarly, the ice-sheet altimetry mission requirements are less stressing than for the laser ranging mission.

The technology of diode-pumped solid-state lasers is one in which DARPA, DOE, and the Brilliant Pebbles program have made substantial progress in recent years (Dube, 1990). For example, diode-pumped infrared and blue-green lasers with tens of watts of average power are now realistic hardware options. It seems to us that these developments could be of considerable assistance to accomplishing the missions for which GLRS was proposed. In our opinion, it would be timely to convene a study to assess which GLRS mission requirements could be met by a smaller laser system, and which (if any) of the developments from the DOD community would be most useful in fielding such a system on a satellite. The field of compact solid-state lasers is one in which there is good potential for technology transfer from the DOD community.

2. Synthetic Aperture Radars (SARs).

The international community is planning to launch four synthetic aperture radars between 1991 and 1998. These will fly on ERS-1 and 2, JERS-1, and Radarsat. Although these SARs have a variety of operating parameters to address different geophysical and biological process, all are single frequency, single polarization instruments.

By contrast, the proposed EOS SAR is planned to operate at three frequencies and four polarizations. It therefore has the potential to have much better discrimination, for example for forests and other vegetation types. Since a SAR with these new capabilities has not yet been flown in a satellite, the quantitative benefits of multi-polarization and multi-frequency operation are not yet explored. Small satellite missions can be designed to begin such an exploration in a timely fashion. For example, tropical forest cutting will greatly impact the environment in the next decade and we currently have no comprehensive way of monitoring this process from space. (Optical observations are hindered by clouds and radar observations with ERS-1, etc. have only limited coverage).

In the evolution of synthetic aperture radar as a remote sensing tool, it has become evident that the use of multiple data channels is the next likely route of advance. This can be accomplished by either multiple frequency operation or the use of multiple polarizations at a single frequency, or both. The analogies at optical wavelengths are the multi-spectral scanner or thematic mapper types of instruments. However, a fully polarimetric SAR (e.g., horizontal and vertical polarization plus relative phase) operating at several frequencies is big and expensive, e.g. the proposed EOS SAR (1,100 kg. instrument with $\approx$ 5 kW average battery power). In terms of exploring the utility of multiple SAR data channels, a small satellite with limited capability makes sense. As we shall see, the simplest option is a single frequency SAR with full polarimetric capability.

A number of SAR applications are well recognized, for example vegetation observations (tropical rain forests), hydrological cycle variables (soil moisture, flooded terrain, snow cover, etc.), sea ice coverage and characteristics, and air-sea interaction parameters. Most of these applications are currently based primarily on single frequency, single polarization data sets. Recent research suggests that in many cases multiple frequency and/or multiple polarization data would make the interpretation of observations more accurate and reliable. For example, multiple frequency observations of sea ice readily distinguish between first year and multi-year ice without absolute calibration. As with Landsat multi-spectral data, ratios between data channels are used to good effect without absolute calibration.

Probably the simplest implementation of a multiple-data-channel SAR is the use of a single frequency with fully polarimetric data collection. An example of such a design for a small (340 kg), Pegasus launched satellite is given by the MEDSAT design team (1991). This instrument is an L-band (23 cm) SAR with full polarimetric capability and a 4-look ground resolution of 75 m (similar to Landsat MSS). The instrument, including the antenna, has a mass of 70 kg and a DC power draw of 860 W. It is designed to collect a 50 x 250 km SAR image every other orbit with the ability to store 4 SAR images (as well as 4 x 4-band visible/IR images) on board before downlinking the data. The SAR uses a variety of techniques, including burst-mode to conserve power and make a small satellite deployment possible. Power and mass are the primary constraints. Multiple polarization (as opposed to multiple frequency) was chosen as the lowest mass and power method of obtaining multiple data channels. The multiple polarization mode is obtained by pairs of radiating patches on the microstrip antenna shown in Figure 1 below. Multiple frequency mode would require an additional set of transmit receive modules and other items as well as a second set of radiating patches. The main power considerations are the peak discharge rate allowed and the time needed to recharge batteries after periods without sunlight. As a SAR image is improved, i.e. contains more and higher resolution pixels, the power required is increased. Hence, some hard choices must be made in order to keep power consumption low. For example, resolution and swath area must be carefully selected.

We conclude that a small satellite SAR is possible and can explore the

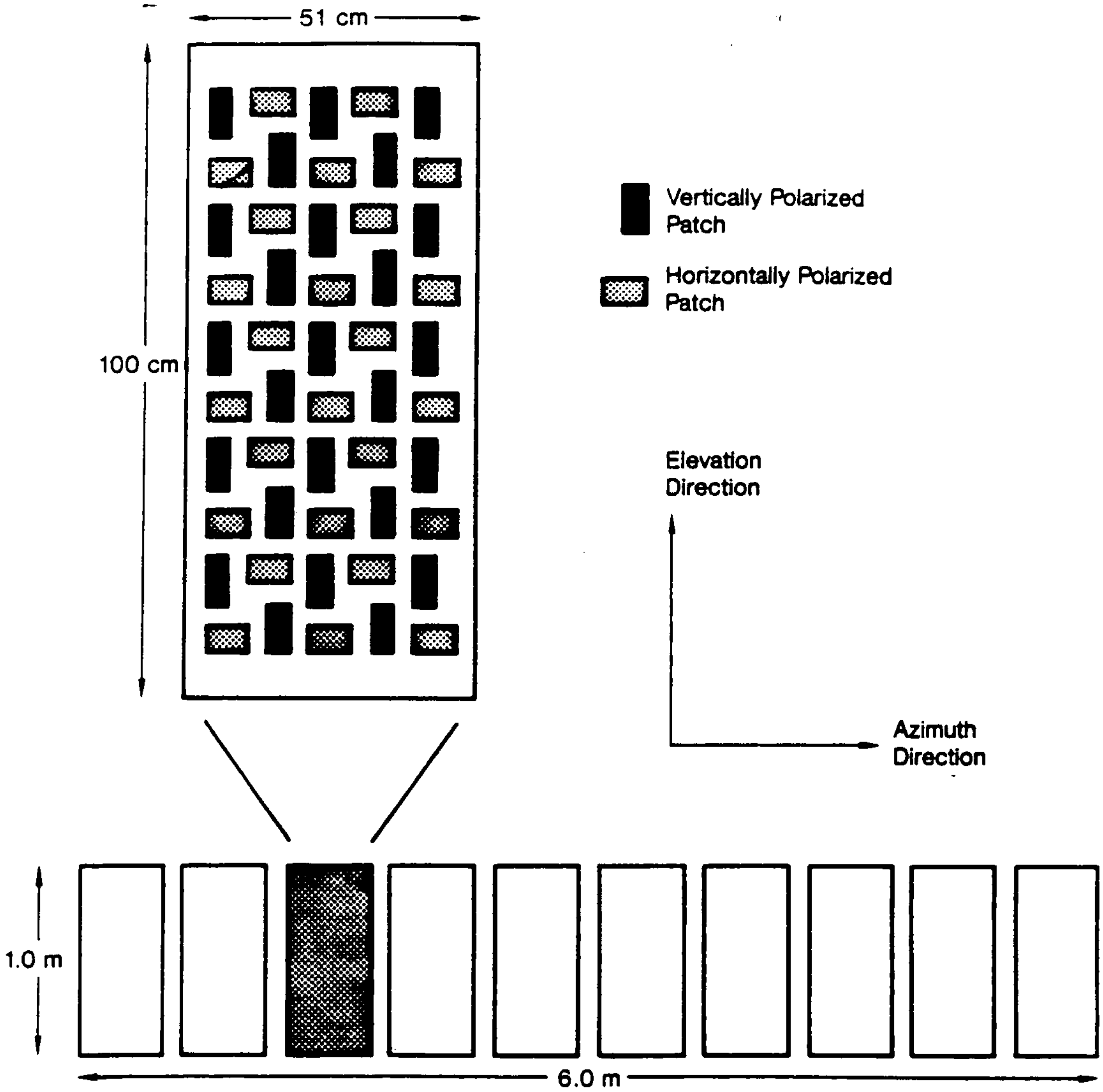

Figure 1. a) Multiple polarization SAR antenna for a small satellite SAR. Source: Medsat Design Team (1991).

utility of multiple SAR information channels. Multiple polarization SAR is less costly to implement in terms of mass and power than multiple frequencies. It is suggested that a small number of sites be covered frequently with significant ground truth, rather than attempting global coverage.

Preliminary design work by TRW and others has resulted in innovative concepts for small SARs, as has the Medsat project (1991). This is a fruitful area for further research.

3. A High Resolution Imaging Spectrometer (HIRIS).

The HIRIS instrument, now tentatively scheduled for EOS A-2, is a high spectral and spatial resolution imaging spectrometer. It has a 30 meter pixel size for imaging, and a spatial swath that is 24 km across. It also has 10 nm spectral sampling resolution, covering the wavelength range from 0.4 microns to 2.45 microns in 192 spectral bands. HIRIS is projected to weigh many hundreds of kilograms, and to consume several hundred watts of power.

HIRIS scientific missions are very varied. They include the study of biological processes such as vegetation, chlorophyll concentration, leaf properties, and biomass distributions over land, and of chlorophyll concentration, absorption, and backscatter coefficients over ocean. In addition, it will be able to address several cloud characteristics as well as aerosol optical depth, precipitable water, and column density of ozone.

DARPA (Demitry, 1991) and the Brilliant Pebbles program (Ledebuhr, 1991) have both proposed lighter weight imaging spectrometers that would have some, but not all, of the functionality of HIRIS in a package suitable for a small satellite. Figure 2 illustrates a candidate design from the Brilliant Pebbles program, to make the point that with a system that is physically small, one has the possibility of gaining increased functionality by having two or three such instruments on a spacecraft, each with somewhat different

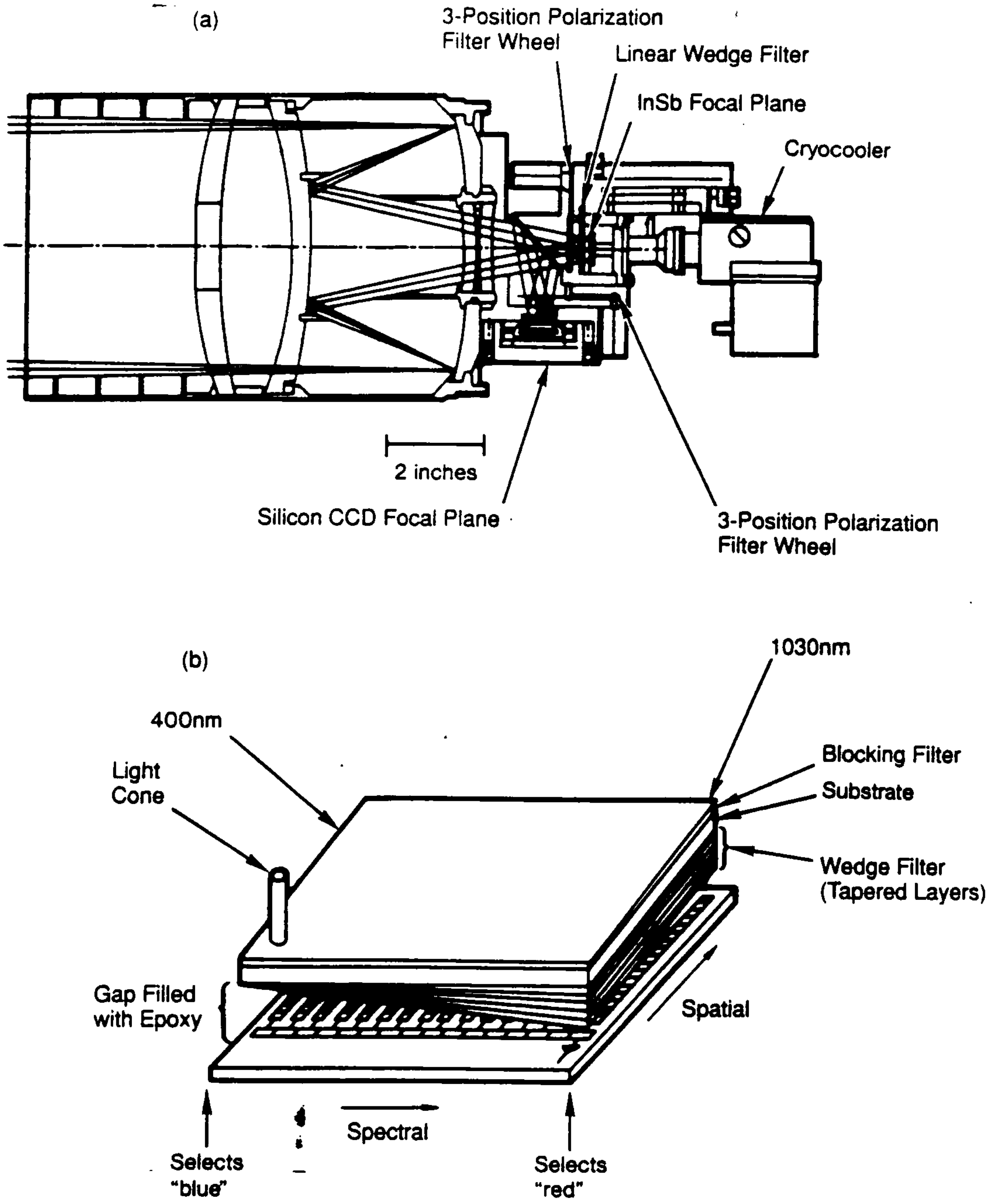

Figure 2. a) Conceptual optical design for linear wedge spectrometer. b) Wedge filter concept. Source: Ledebuhr (1991).

design parameters.

In general we think that imaging spectrometers are a promising small-satellite application.The spectrometers proposed by both DARPA and the Brilliant Pebbles program are in very preliminary stages of development. They should be regarded as illustrative of the range of smaller instruments that could take on some of HIRIS's functionality on a small satellite. Now that these two concepts have been proposed, it is important for their proposers to interact much more strongly with the global change community before fixing on a specific set of capabilities, size, and weight for the instruments.

HIRIS was designed to address a wide variety of scientific missions, not all of which can be addressed from a smaller platform. Hence there needs to be an evaluation of which of the HIRIS missions have the highest priority in the national global change research program, so that the candidates for small-satellite imaging spectrometer implementations can focus on the most important HIRIS science goals. There also needs to be a dialogue on the issue of whether such an imaging spectrometer needs to fly in formation with EOS in order to provide congruent or simultaneous data, what kind of global and orbital coverage is required for each of the missions of the spectrometer, and what levels of calibration and instrument lifetime are optimum for each of the most important missions.

4 GENERAL COMMENTS ON THE APPLICATION OF DOD TECHNOLOGIES TO THE GLOBAL CHANGE RESEARCH PROGRAM

It is clear that the Department of Defense, DARPA, and the DOE have developed several technologies that could be generically useful in small satellites to study global change. Compact and lightweight spacecraft support technologies, smaller instrument packages, and improved solar cells are all examples.

However, there is not a storehouse of "off-the-shelf" DoD instruments that can be used "as-is" for global change research. DoD instruments were optimized for a specific set of applications, which do not in general match the mission requirements of instruments for the global change program.

Hence what is needed for a successful "technology transfer" from the DoD community to the global change research program is much more focus on how to use these capabilities for the highest-leverage issues in climate studies. To accomplish this, there will have to be much more communication and collaboration between the DoD and the climate communities than there has been to date. In a real sense a technical dialogue must be established between the two (previously separate) communities. This dialogue will serve two purposes: to ensure that the DoD instruments and technologies are used to solve the problems that really *matter* to global change, and to make the global change community aware of the capabilities that this technology makes available.

In addition, at least some members of the DoD community must spend more time becoming conversant in global change science itself: immersing themselves in the issues, understanding the scientific priorities and the current observational status. To date, we estimate that only a few man-years have been devoted to this effort so far in the DARPA, DOE, and SDIO groups that are proposing small satellite applications. Most of the instruments proposed by the DoD community have little or no "heritage" in space flight, and many of the instruments do not exist at all except in the form of viewgraphs. Considerable work is therefore needed to establish the credibility of the various small satellite instrument concepts. In order to successfully move one or two of these proposals from the "viewgraph stage" to the more mature stages of concept definition, engineering studies, and (after peer review) the construction of laboratory prototypes, we estimate that at least 10 or 20 man-years will be needed. This is not a huge committment of time by usual DoD standards, but nevertheless it needs to be recognized up front that some DoD technical people are going to have to devote themselves to global change research in order to accomplish a successful technology transfer in this field.

In the sections above we have focussed on instruments. There are, of course, other aspects of space technology that are important for small satellites in a global change role. DARPA's small satellite program seeks to make it possible for 50% or more of a small satellite's payload to be used for instrumments – the current rule of thumb is about 25% (Demitry, 1991). DoD/DOE technology in data storage, processing, transmission, reception and interpretation are also potentially useful. For example, the TODS (tactical optical disk system) is a small, light, low power optical disk which stores 2.4 G bits using 35W of power and a mass of 8 kg. This has been developed by DoD for aircraft and is an excellent candidate for use on small satellites. This topic of light weight DoD- developed spacecraft support systems is discussed in more detail in Section ?.

REFERENCES

1. Demitry, L. (1991), presentation to DOE EOS-A Engineering Review Committee, July 1991, La Jolla, CA.
2. Dube, G. (1991), editor, "Solid State Lasers", Proceedings S.P.I.E. **1223**.
3. Hansen, J., W. Rossow, and I. Fung (1990), "The Missing Data on Global Climate Change", Issues in Science and Technology **VII**, pages 62-69.
4. Ledebuhr, A. (1991), presentation to JASON summer study, June 1991, La Jolla, CA.
5. Medsat Design Team (1991), "Project MEDSAT", Aerospace Engineering and Atmospheric, Oceanic, and Space Science Departments, The University of Michigan, Ann Arbor, MI.
6. Vitko, J., R. Abbink, T. Axelrod, C.A. Boye, I. Lewis, and P. Weber (1991), Presentation to JASON summer study, June 1991, La Jolla, CA.