THE PICASSO-CENA MISSION

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ABSTRACT

Current uncertainties in the effects of aerosols and clouds on the Earth radiation budget limit our understanding of the climate system and the potential for global climate change. PICASSO-CENA is a recently approved satellite mission within NASA's Earth System Science Pathfinder (ESSP) program designed to address these uncertainties. The PICASSO-CENA mission includes the first satellite lidar dedicated to atmospheric sensing - optimized for studies of the climate effects of aerosols. PICASSO-CENA will serve as a pathfinder for future satellite lidar instruments dedicated to this and other purposes. PICASSO-CENA will be flown in formation with the EOS Aqua and CloudSat satellites to provide data coincident with the instruments on EOS Aqua and the cloud profiling radar on CloudSat. PICASSO-CENA will benefit retrievals from Aqua instruments through the detection of aerosols and subvisible clouds and the unambiguous determination of cloud height by the lidar. Cloud observations from the lidar and the CloudSat radar will be complementary, together encompassing the variety of clouds found in the atmosphere. The mission will demonstrate the benefits of including lidar on future remote sensing satellites. PICASSO-CENA is planned for a three-year mission beginning in early 2003 and is being developed within the framework of a collaboration between NASA and CNES.

1. INTRODUCTION

Recent assessments by the international science community (National Research Council, 1996; IPCC, 1996) have concluded that the largest uncertainties in our ability to predict future climate change are associated with the radiative effects of aerosols and clouds. The Pathfinder Instruments for Cloud and Aerosol Spaceborne Observations - Climatologie Etendue des Nuages et des Aerosols (PICASSO-CENA) mission was recently chosen as the third satellite mission within NASA's Earth System Science Pathfinder (ESSP) program. This mission will address these uncertainties with a unique suite of active and passive instruments. The Lidar In-space Technology Experiment (LITE) in 1994 demonstrated the potential of space lidar for studies of aerosols and clouds (Winker et al., 1996). PICASSO-CENA builds on this experience with a payload consisting of a two-wavelength polarization-sensitive lidar, an oxygen A-band spectrometer (ABS), an imaging infrared radiometer (IIR), and a wide field camera (WFC). Data from these instruments will be used to measure the vertical distributions of aerosols and clouds in the atmosphere, as well as optical and physical properties of aerosols and clouds which influence the Earth radiation budget. PICASSO-CENA is being developed within the framework of a collaboration between NASA and CNES. CNES will provide the spacecraft, the IIR, spacecraft operations, and contributes to PICASSO-CENA science activities.

The afternoon satellite of the NASA Earth Observing System (EOS Aqua, formerly EOS PM) and CloudSat are two NASA missions with science objectives related to those of PICASSO-CENA. The science focus of EOS Aqua is on clouds and the hydrologic cycle. EOS Aqua is scheduled for a five-year mission starting in late 2000. The CloudSat mission, whose primary instrument is a 94 GHz cloud profiling radar, has recently been selected as the fourth ESSP mission. PICASSO-CENA and CloudSat will be launched together in early 2003 on a Delta II launch vehicle. PICASSO-CENA and CloudSat will fly in formation with EOS Aqua to provide a comprehensive set of coincident measurements of atmospheric state, aerosol and cloud properties, and radiative fluxes. This combined dataset will allow the fundamental advances in our understanding of the links between aerosols, clouds, and radiation necessary to accurately assess future climate change.

2. SCIENCE OBJECTIVES

2.1 Aerosol Radiative Forcing. Atmospheric aerosols *directly* affect the Earth's energy balance by

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absorbing and scattering shortwave (SW) solar radiation, and by absorbing and emitting longwave (LW) infrared radiation. Aerosols *indirectly* affect this balance by influencing the properties and processes of clouds through their role as cloud condensation nuclei. A simple way to quantify the importance of a potential climate change agent is in terms of a *radiative forcing*, which is the perturbation to the energy balance of the Earth-atmosphere system (in W/m^2) due to a change in the agent. Greenhouse gases are positive forcers and warm the climate. Aerosols generally have a cooling effect, although the cooling effect decreases with increasing aerosol absorption and can become a net warming for sufficiently absorbing aerosols.

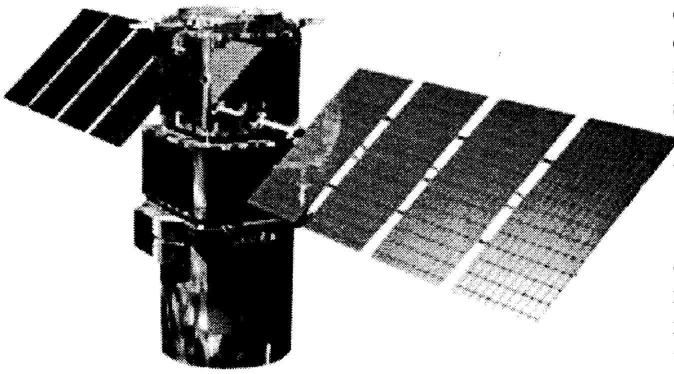

Figure 1. The PICASSO-CENA satellite.

The globally averaged forcing from aerosols is significant with respect to that of greenhouse gases (Charlson et al., 1991) but the magnitude of aerosol forcing is highly uncertain. While greenhouse gases are well-mixed globally, tropospheric aerosols are highly variable in time and space. The direct forcing from aerosols tends to be largest over the continents, where anthropogenic sources are located and sensing with passive instruments is most difficult. These large regional forcings can produce equally large remote surface temperature responses by modulating the atmospheric general circulation and may be masking the warming effect of increasing greenhouse gases. Recent modeling studies have shown that the agreement between the geographic pattern of temperature change observed in the climate record and the patterns predicted by climate models which do not consider aerosol radiative forcing improves significantly when the forcing from anthropogenic sulfate aerosol is included in the models (Santer et al., 1995; Barnett et al., 1999).

Current observations of the global distribution of aerosol in the lower troposphere come from passive radiometer instruments such as AVHRR and TOMS. These instruments have very limited capabilities over land, are not sensitive to low concentrations of aerosol even over the ocean, and provide no information on the vertical distribution of aerosol. Due to the inadequacy of this existing satellite aerosol record, estimates of aerosol forcing have been based on calculations from chemical transport models (CTMs). The large uncertainties in model estimates of forcing are due to the fact that many of the input parameters are not well-known and few are measured. Additionally, there are no existing global observations of aerosol direct forcing, aerosol properties, or aerosol source strengths against which these model estimates may be checked. Simultaneous observation of aerosol properties by PICASSO-CENA and radiative fluxes and atmospheric state from EOS Aqua will provide measurements of direct aerosol forcing and the key independent variables that control it. For the first time, it will be possible to test the assumptions and predictions of CTMs.

In addition to direct radiative forcing, aerosols also produce an indirect radiative forcing by modifying the reflectance and lifetime of clouds. The magnitude of this forcing is highly uncertain due to the lack of appropriate global data sets. As discussed below, combining simultaneous measurements from PICASSO-CENA and from CERES and MODIS on EOS Aqua will provide an improved data set for the determination of these effects.

2.2 Clouds and Radiation. PICASSO-CENA will also improve our knowledge of the radiative effects of clouds. The largest uncertainty in predicting the climate response to a specific radiative forcing is due to uncertainties in the modeling of cloud-radiation interactions. Understanding the Earth radiation budget requires observations of radiative fluxes at the top of the atmosphere (TOA), at the surface of the Earth, and at levels within the atmosphere. Cloud imager and CERES broadband radiation observations on EOS Terra and EOS Aqua will provide estimates of TOA fluxes to an accuracy approaching 10 W/m^2 for instantaneous measurements and 1.5 W/m^2 for monthly zonal and global means (Wielicki et al., 1995). However, uncertainties in estimates of mean radiative fluxes at the Earth's surface will be much larger, primarily due to the limitations of passive sensors in characterizing the vertical distribution of multilayer clouds. This is an especially critical problem in assessing the separate roles of the atmosphere and ocean in transporting heat from the tropics to the polar regions. PICASSO-CENA and EOS Aqua will together provide the systematic collection of coincident TOA flux and multilayer cloud observations required to significantly reduce uncertainties in cloud-radiation interactions.

Inadequacies in the representation of cloud-radiation feedback processes in models represents a second source of uncertainty in cloud-radiation interactions. The fundamental problem is in modeling the cloud feedback loop shown in Figure 2. The largest uncertainties involve the use of models to (a) predict cloud properties based on atmospheric state, and to (b) use these cloud properties to calculate radiative fluxes. Nearly simultaneous observations of all three parts of the cloud feedback loop are necessary to accurately predict the future impact of greenhouse gases. Near simultaneity is required because of the short time scales and nonlinear relationships typical of cloud processes. Therefore, the ability of cloud models to reproduce feedback physics cannot be adequately tested with observations that are decoupled in space and time.

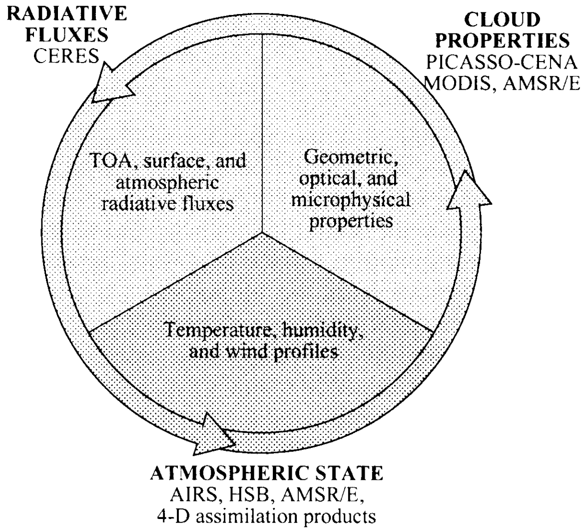

Figure 2. Connections between atmospheric state, cloud properties, and radiative fluxes and the instruments required to observe the relevant parameters.

Simultaneous, coincident data from PICASSO-CENA, CloudSat, and EOS Aqua will allow by far the most complete closure of this feedback loop possible in the near future. EOS Aqua will provide atmospheric state information and TOA radiative fluxes; PICASSO-CENA will provide coincident information on cloud altitude, thickness, and optical and microphysical properties; and CloudSat will provide the height and thickness of deep cloud and information on cloud water and ice contents. These combined measurements will be a fundamental scientific advance in the ability of the climate research community to improve our understanding of global cloud-climate feedback mechanisms.

3. INSTRUMENT SUITE

The PICASSO-CENA satellite is illustrated in Figure 1. The primary features are the PROTEUS spacecraft bus, provided by CNES, the payload housing, and a 1-meter diameter receiver telescope. The instrument payload (Figure 3) consists of a set of four complementary, nadir-viewing instruments:

- A two-wavelength, polarization-sensitive lidar providing high resolution vertical profiles of aerosol and cloud properties. The change in backscatter between the two wavelengths allows a classification of aerosol size. The ratio of orthogonally polarized components of the 532 nm backscatter allows the identification of cloud ice/water phase.
- An oxygen A-band Spectrometer (ABS) having sufficient spectral resolution (0.5 cm^{-1}) to resolve the line structure of the oxygen A-band, centered at 765 nm. ABS spectra combined with lidar profile data are combined to retrieve aerosol and cloud optical depth, aerosol absorption, and cirrus asymmetry parameter (Stephens and Heidinger, 1999).
- An Imaging Infrared Radiometer (IIR) providing calibrated radiances at 8.7 μm , 10.5 μm, and 12 μm. These wavelengths are chosen to optimize joint lidar/IIR retrievals of cirrus emissivity and particle size. The IIR images a swath of 64 km with a spatial resolution of 1 km.
- A Wide Field Camera (WFC) covering the 620 nm to 670 nm spectral region providing images of a 60 km swath with a spatial resolution of 125 meters. The WFC provides assessments of homogeneity within the ABS footprint, meteorological context, and allows highly accurate spatial registration between PICASSO-CENA and EOS-Aqua.

Performance specifications of these instruments are listed in Table 1.

Characteristic	Value
lidar	
wavelengths	532 nm - polarization sensitive 1064 nm - intensity
pulse energy	110 mJ each wavelength
footprint	100 m
spatial resolution	250 m horiz, 30 m vert
ABS	
spectral range	763-769 nm
spectral resolution	0.5 cm^{-1}
footprint	1 x 1 km^2
WFC	
spectral range	620-670 nm
IFOV/swath	125 m/ 60 km
IIR	
wavelengths	8.7 μm, 10.5 μm, 12.0 μm
spectral resolution	0.8 μm
IFOV/swath	1 km/64 km

Table 1. PICASSO-CENA instrument characteristics.

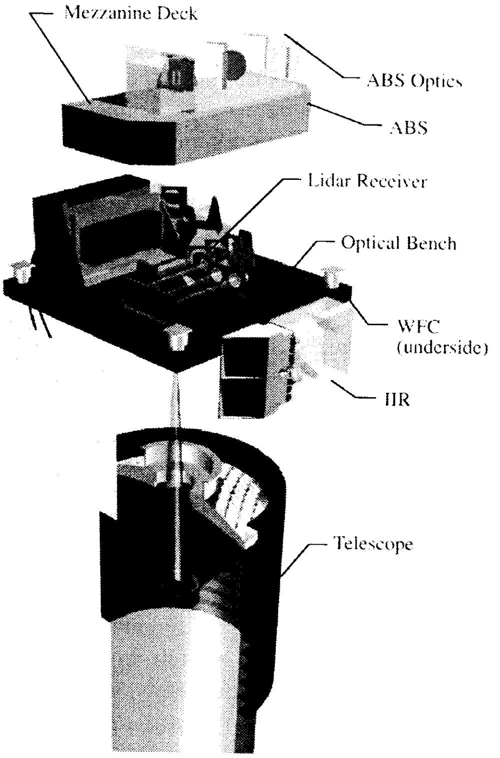

Figure 3. Expanded view of the PICASSO-CENA instrument payload.

4. OBSERVING STRATEGY

The PICASSO-CENA orbit was chosen to provide space-time coincidence with EOS Aqua observations. EOS Aqua is in a sun-synchronous 705-km circular orbit with an ascending node equatorial crossing time of 13:30 local time. PICASSO-CENA will fly at the same altitude as EOS Aqua, and its orbit will be maintained so that a point on the ground will be observed by the two platforms within 6 min of each other. This timing constraint, based on the results of sampling studies, ensures that the TOA radiative fluxes from the clouds observed by the two platforms will differ by less than 10 W/m^2, which is the expected 1-sigma uncertainty in the instantaneous CERES measurements themselves. A combination of spacecraft pointing knowledge and correlation of WFC and IIR imagery with MODIS scenes will allow a determination of the spatial co-registration of the two data sets to better than 250 m during the day and 1000 m at night.

The CloudSat satellite will fly in formation with the PICASSO-CENA satellite, at a separation of about 60 seconds. The two satellites will be injected into an orbit inclined slightly with respect to the orbit of EOS Aqua, so that over the course of 3 years they will slowly precess across the viewing swath of the EOS Aqua instruments. Table 2 indicates how data from the instruments on the PICASSO-CENA, EOS Aqua, and CloudSat satellites will be used to address the climate impacts of aerosols and clouds. The precessing orbit of PICASSO-CENA will provide coincident observations over a wide range of EOS Aqua instrument viewing zenith angles, for all seasons and atmospheric conditions. By flying in formation with EOS Aqua, PICASSO-CENA and CloudSat will provide the measurements necessary to derive the links between aerosols, clouds, and radiation that are needed to assess future climate change.

5. MEASUREMENT OBECTIVES

The data products to be available from PICASSO-CENA and the instruments from which they are obtained are listed in Table 3. In many cases, data from two or more instruments will be combined to provide improved retrieval performance. The lidar

Science	Measurement	Instrument
1. Direct Aerosol Forcing	aerosol profiles at 532 nm and 1064 nm; lidar depolarization	lidar
	aerosol optical depth and absorption	lidar, ABS, WFC
	broadband radiances	CERES
2. Indirect Aerosol Forcing	aerosol/cloud heights	lidar
	aerosol optical depth	lidar, ABS, WFC
	cloud reflectance and droplet size	MODIS
3. Longwave Radiative Forcing	cloud heights	lidar, CPR
	lidar depolarization profiles	lidar
	cirrus emissivity and particle size	lidar, IIR
	broadband radiances	CERES
	cloud properties	MODIS, AIRS, AMSR, CPR
4. Cloud Radiative Feedback	as in (3), plus: cirrus optical depth and asymmetry parameter	as in (3), plus: lidar, ABS

Table 2. Connections between science objectives and measurements.

Measurement	Lidar	ABS	WFC	IIR
Aerosol profiles	●			
Aerosol optical depth (night)	●			
Aerosol optical depth and single scatter albedo (day)	●	●	●	
Cloud height and thickness	●			
Cloud optical depth (night)	●			
Cloud optical depth and cirrus asymmetry parameter (day)	●	●	●	
Cloud ice/water phase	●			
Cirrus emissivity	●			●
Cirrus particle size	●			●

Table 3. PICASSO-CENA Cloud and Aerosol Measurements

will be used for cloud-clearing and scene identification and will provide cloud height information for retrievals from the passive instruments. The data products will be archived at the NASA Langley Research Center DAAC.

5.1 Aerosol Measurements. The single most important advance that PICASSO-CENA provides is its ability to measure aerosols accurately over bright and heterogeneous land surfaces and under other conditions which are difficult or impossible for passive sensors, such as above clouds or beneath thin cirrus. Combined with EOS Aqua, PICASSO-CENA will provide the first global and regional measurements of direct aerosol forcing and the independent variables – aerosol vertical distribution and optical properties – that control it. Among the key parameters that will be derived are:

- *Aerosol optical depth* τ_a. Retrieval of τ_a from lidar data generally requires the assumption of a value for the ratio of aerosol extinction to aerosol 180°-backscatter. Uncertainty in the value of this ratio typically limits the accuracy to which τ_a can be retrieved from lidar to no better than 30%. At low optical depths ($\tau_a < 0.04$) this is sufficiently accurate for calculations of aerosol radiative forcing, but it is not adequate in situations of high aerosol loading which produce the most significant regional forcings. At these higher optical depths, joint lidar-ABS retrievals of τ_a will provide improved accuracy.

- *Single scatter albedo*, ω. The degree to which aerosols absorb radiation has a significant impact on the magnitude and sign of direct aerosol forcing. Currently, aerosol absorption cannot be measured remotely from space and in situ measurements are sparse. The combination of lidar and ABS data will be used to derive the first global maps of ω.

- *Aerosol indirect radiative effects* can be estimated from a statistical analysis of ensembles of broken, low-level, single-layered cloud systems which are embedded in aerosol plumes of various types. Kaufman and Fraser (1997), for example, have used AVHRR observations to deduce statistical relationships between τ_a, cloud droplet size, and cloud reflectance associated with smoke plumes over the Amazon Region. This same approach is applicable to MODIS data. PICASSO-CENA will allow improved assessments of aerosol indirect forcing through improved aerosol measurements as well as by unambiguously distinguishing clouds embedded in an aerosol layer from those located above or below the layer

5.2 Cloud Measurements. Current cloud retrievals from passive satellite sensors detect only an upper cloud layer or retrieve one equivalent cloud layer. In contrast, Figure 4 indicates the capabilities of lidar to observe the vertical structure of multi-layer cloud. The lidar beam is blocked by dense boundary layer clouds and deep convective clouds. LITE demonstrated that spaceborne lidar can provide accurate measurements of cloud vertical structure down to an altitude of 1 km in 70% of all cloud cases.

The major source of the uncertainty in surface flux estimates is due to a lack of knowledge of the degree of cloud overlap in multilayered cloud systems (Charlock et al., 1994). Both surface observations (Hahn et al., 1982) and recent Lidar In-Space Technology Experiment (LITE) data (Winker, 1998) indicate that roughly half of all cloud systems are multilayered. By combining spaceborne lidar measurements of cloud vertical structure with simultaneous CERES broadband radiation and MODIS cloud optical property measurements from EOS Aqua, estimates of surface LW flux and LW heating rates within the atmosphere will be significantly improved. Additional improvement will be realized from combining coincident observations of deep clouds from CloudSat with PICASSO-CENA and EOS Aqua observations.

The new measurement capabilities of PICASSO-CENA and CloudSat, when combined with EOS Aqua observations, will also enable significant progress in our understanding of cloud-radiation feedbacks. The completeness of this set will be

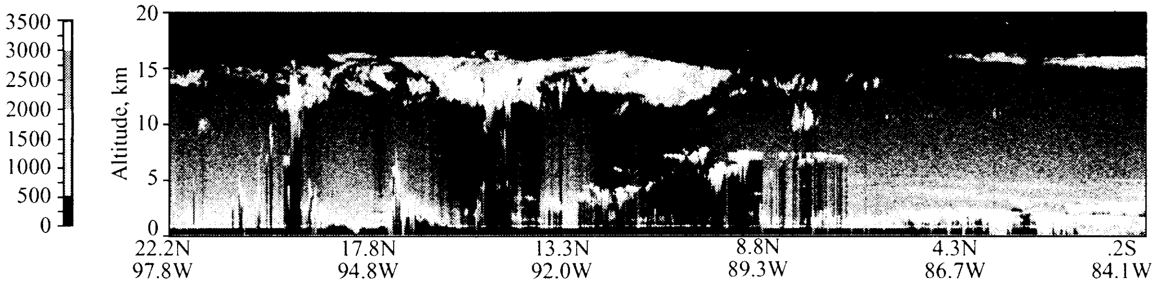

Figure 4. LITE 532 nm backscatter signal showing multiple cloud layers observed over the tropical Pacific Ocean on September 14, 1994.

unprecedented and demonstrates the complementarity of the measurements: PICASSO-CENA for clouds of small to moderate optical thickness and EOS Aqua and CloudSat for optically thicker clouds.

New types of cloud/radiation feedback studies will be possible for the first time using PICASSO-CENA data, three examples are:

- Combination of data from the PICASSO-CENA lidar and ABS permit the first measurements of ice cloud asymmetry parameter g_{ice}, which will provide critical information on the relationship between cloud optical depth and cloud reflectance.

- PICASSO-CENA will provide new data to address the broadband SW and LW radiative forcing of optically thin clouds. Both the infrared emissivity, ε_c,, and particle size, r_{eff}, of cirrus can be estimated from the large difference in absorptivity of ice between the three IIR channels (Parol et al., 1991). Unambiguous cloud heights provided by the lidar will allow more accurate retrievals of r_{eff} than have been possible in the past. CERES will provide the matched TOA radiative fluxes necessary to evaluate the radiative forcing as a function of thin cirrus cloud properties. PICASSO-CENA measurements will also improve and validate MODIS and AIRS cloud property retrievals for optically thin clouds such as subvisual cirrus (Winker and Trepte, 1998) and jet contrails (Smith et al., 1998).

- Measurements of the linear polarization of the lidar return signal will provide the first spaceborne vertical profiles of cloud particle phase, allowing a determination of the vertical distribution of cloud particle liquid and ice phases.

6. SUMMARY

The PICASSO-CENA mission is designed to provide necessary observations on aerosols and clouds which are missing from EOS. The comprehensive combined data set to be acquired by PICASSO-CENA, CloudSat, and EOS Aqua will allow the fundamental scientific advances in our understanding of the links between aerosols, clouds, and radiation which are necessary to accurately assess future climate change. PICASSO-CENA will also demonstrate the feasibility and usefulness of satellite lidar for atmospheric studies. The PICASSO-CENA lidar is a simple instrument focused on one particular application and represents the first step toward the more sophisticated lidars which will be developed in the future. Improved systems will be developed to better address the radiation budget problem as well as other problems not addressed by PICASSO-CENA, such as winds, and the distribution of ozone and water vapor in the troposphere. The benefits of the unique information provided by lidar, alone and in combination with other instruments, will soon be recognized as an essential component of satellite missions designed for atmospheric studies.

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