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TITLE SMALL SATELLITE RADIOMETRIC MEASUREMENT SYSTEM

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SMALL SATELLITE RADIOMETRIC MEASUREMENT SYSTEM*

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A critical need for the U. S. Global Change Research Program is to provide continuous, well-calibrated radiometric data for the Earth's radiation budget. This paper describes a new, compact, relatively light-weight, adaptable radiometer which will provide both spectrally integrated measurements and data in selected spectral bands. The radiometer design is suitable for use on small satellites, aircraft, or remotely piloted aircraft (RPAs). An example of the implementation of this radiometer on a small satellite is given. Significant benefits derive from simultaneous measurements of specific narrow (in wavelength) spectral features; such data may be obtained by combining LARI with a compact spectrometer on the same platform. Well-chosen satellite orbits allow one to use data from other satellites (e.g. DMSP) to enhance the data product, or to provide superior coverage of specific locations.

Introduction

Understanding of global climate changes demands, at the very least, accurate measurements of the radiative fluxes through the top of the atmosphere as a function of space and time, and covering the full range of ambient conditions. Indeed, a measure of the success of global circulation models (GCMs) is to compare the predicted energy balance from the codes with observations¹. Information on the global energy balance was provided by the Earth Radiation Budget Experiment (ERBE) instruments². However, the ERBE scanners are no longer providing data, and the follow-on experiment, CERES, is scheduled to fly no earlier than 1997. Thus a large data gap exists in measuring the global radiation balance at this critical time.

Another issue is to investigate radiative fluxes over a given site, combined with a full complement of measurements of ambient conditions. This would lead to a better understanding of the processes which underlie the observed fluxes, and to better parameterizations for inclusion into climate models.

Such a study is being undertaken by the US DOE Atmospheric Radiation Measurements Program (ARM)³, with the first site to be located in the mid-Western USA (Oklahoma / Kansas). Operation at this first site is scheduled to start in 1992. Further sites will be established in the Western Pacific Ocean, the North Slope of Alaska, and elsewhere, at annual intervals thereafter. We have examined the efficacy of choosing satellite orbits which optimize coverage over at least these three sites.

This paper introduces the design of the Los Alamos Radiometric Instrument (LARI): a new, compact, relatively light-weight, adaptable radiometer for these important measurements, together with some potential applications including operation on small satellites, and in concert with other measurement systems. The instrument includes well-calibrated total, shortwave, and contiguous, spectrally resolved channels, thus providing important information to the community⁴. The design allows implementation on a satellite, an aircraft, or remotely piloted aircraft (RPA) with relatively minor modifications. However, the design philosophy for satellite, aircraft, and RPA radiometers is the same: namely, to provide a compact, low power, well-calibrated instrument with the desired spatial and wavelength coverages.

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Experiment Design Considerations

Accurate measurements of the Earth's radiation balance are required for understanding of the processes controlling that balance. The measurement requirements are discussed in detail by the National Research Council's Committee on Earth Sciences (NRC/CES)⁴. The spectral coverage must include the range from about 0.3 to 4 μm for albedo studies, and approximately 4 to $\geq 50 \mu\text{m}$ for the longwave (thermal) flux. Some spectral resolution is desired to establish the actual composition of the atmosphere at the time of measurement. The required accuracy is extreme: as a simple basis, consider that doubling the CO_2 concentration in the atmosphere is predicted to have a net effect of only 2 - 4 $\text{W}\cdot\text{m}^{-2}$ compared to an annual average insolation of $\sim 340 \text{ W}\cdot\text{m}^{-2}$. The data also are to be sufficiently accurate to detect decadal climate trends. The mean accuracies suggested by the NRC/CES are 5% for the short-wave and 5 $\text{W}\cdot\text{m}^{-2}$ for the long-wave over annual cycles with 1-month resolution.

Because of variations in solar zenith angle, temperature, humidity, clouds and atmospheric composition, one wishes to make observations over the full earth in sufficiently short timescales⁵. Continuity and overlap of measurements is also important to uncover any systematic offsets between satellite instruments. Thus, this problem is an excellent match to small satellites, with their attributes of relatively low cost and flexibility of launching. One can conceive of a set of three small satellites providing the appropriate diurnal and global coverage for the global radiation balance issue, or a similar set optimized for coverage of ARM sites.

LARI Instrument Description

The design of the Los Alamos Radiometric Instrument shown in Figure 1 is optimized for aircraft applications: the satellite version can be considerably simpler. (The aircraft version needs to operate in rather rapidly changing conditions as the aircraft flies through various

conditions. For example, the ambient temperature at 60,000 ft is a hundred degrees (C) colder than at the ground, and humidity varies over a wide range.) The input optic (lower left side of Fig. 1) consists of a pair of mirrors, mounted on a rotating scanner drum, and oriented at 45° to each other to provide almost complete cancellation of polarization effects. In addition to observing the desired scene, this scanner also accesses the on-board calibration sources (shown schematically as a rectangle near the scanner drum), thereby providing a complete instrument calibration on every scan. The modified Gregorian telescope determines the instantaneous field-of-view (IFOV) and allows physical separation between the input section of the telescope and the spectral analysis and detection volume (at the upper right of Fig. 1). These volumes are linked by a small aperture, allowing thermal and environmental stability for the prisms and detectors over long time-scales. A chopper is used at this aperture, since the pyroelectric detectors observe only *changes* in power: thus each individual measurement is referred to the chopper blade, with a full instrument calibration referenced to the on-board calibration sources on every complete rotation of the input optics scanner. Nominal design values for LARI in a $\sim 800 \text{ km}$ orbit include a nadir pixel size of 20-30 km, with cross-track scanning to 1500 km from nadir; the scan rate is sufficiently fast to spatially oversample. Various satellite maneuvers can be used to increase the viewing range of the instrument: one could, for example, rotate the satellite to obtain along-track scanning; such a data set would contribute to bi-directional reflectivity models.

After passing through the aperture, the radiation is recollimated, and then divided into several channels. The first channel is the total radiation channel, in which a geometrically determined fraction of the input power is directly focused on a detector, which measures the wavelength integral over the entire range of 0.2 to $>50 \mu\text{m}$ (this range being determined by the characteristics of the optics and detectors).

A parallel "short-wave" channel is identical, except the detector is filtered with a Suprasil (or similar) window, selecting radiation in the 0.2 to $\sim 4\mu\text{m}$ range. These two channels duplicate the functionality of the most frequently used ERBE channels; the wavelength-integrated long-wave radiation is typically obtained by subtracting the wavelength-integrated short-wave channel from the total.

While these two broad channels allow a separation of "solar" and "thermal" radiation, one requires spectral resolution to point to the causes of changes in these integrals. For example, with even crude spectral resolution, one can separate the black-body equivalent temperature and the major absorption features due primarily to CO_2 , O_2 , O_3 , H_2O , etc.. This radiometer includes this capability. Part of the radiation is dispersed by two side-by-side prisms, and is then incident upon a linear array of detectors, with the dispersion and detector dimensions chosen to give wavelength bands with specific dominant influences in each band. Figure 2 shows an example of such a selection: there are four contiguous bands (labelled 1,2,3,4) in the "short-wave"; plus five contiguous bands (labelled 5-9) in the "long-wave" region with dominant absorbing species indicated. The choices of spectral bands are, of course, limited by the available optical materials and by the detector characteristics. The two prisms are made of different optical materials, (e.g. quartz and CsI) to enable coverage of the full spectrum (0.2 to $>50\mu\text{m}$) in transmission.

Light in the upper atmosphere can be highly polarized⁶. The LARI optical system is designed for low sensitivity to polarization: in addition to the polarization cancelling input scanner, the optics are used at small (near-normal) angles.

Pyroelectric detectors have been chosen for a number of reasons. They are thermal detectors, which, with appropriate coatings, (see, e.g. Refs. 7 and 8) can cover the full wavelength region (0.2 to $>50\mu\text{m}$) with uniform responsivity. They do not require cooling the

chopping frequency is selectable over a reasonable range, sensitivity is more than adequate for our application, and linearity is excellent. Electrical Substitution Radiometers using pyroelectric detectors have proven accurate at the $< 1\%$ level with excellent stability over many years⁹. Pyro-electric detectors have been used successfully both in space^{10,11}, and in aircraft radiometers¹². Recent advances in material science and processing have permitted the production of both linear and two-dimensional arrays¹³.

Accuracy of measurement is of paramount importance. The accuracy goal is one percent for the total and integrated short-wave channels. The radiometer will first be calibrated in a laboratory facility, using well-characterized blackbodies, tungsten lamps in an integrating sphere geometry, and other spectral sources. The calibrations will be ultimately referenced to a cryogenic electrical substitution radiometer¹⁴, and to self-trapping photodiodes¹⁵. The details of the on-board calibrations are dependent on the specific application, but will consist of at least one blackbody (preferably two) plus lamp(s) for the shorter wavelengths. The calibrations require "state-of-the-art" equipment and techniques; they are facilitated slightly by the simultaneously available spectral information and built-in redundancy of checking that the sum of the spectrally resolved channels equals the total channels.

Data Products

As discussed above, LARI is capable of fulfilling all of the requirements for radiation budget measurements as delineated in a number of studies. The instrument generates large quantities of data (35 kbps), which must be stored, sent to one or more ground stations, checked, archived and distributed to analysis centers. Analysis of ERBE data has demonstrated that a large amount of effort is required to translate the radiometer data into a meaningful measurement of the fluxes at the top of the atmosphere¹⁶.

For ERBE, the instantaneous accuracy of the

estimated Earth radiation budget is limited by the uncertainties in identification of the scene type, and in applying the angular dependence models (ADMs). The two major variables are the changes in geographic surfaces and the change in cloud conditions. While one can handle the geography problem reasonably using a geographic map, (ground cover may be assumed to change only on long time-scales, including seasonal changes in deciduous forest, snow cover, etc.) the clouds are highly dynamic, and therefore require simultaneous characterization.

The ERBE analysis dealt with this problem using a "maximum likelihood estimation" (MLE) algorithm for their coarse resolution broadband satellite data (short-wave / long-wave) together with empirical models of angular dependence of radiance. This gives a substantial improvement over the Lambertian Earth and clear/cloudy threshold method used in the inversion of Nimbus-3 and Nimbus-7 Earth radiation budget data. The ERBE cloud determination is based on the ratio between the short-wave ($0.3\text{--}5\ \mu\text{m}$) and longwave ($\geq 5\ \mu\text{m}$) radiances combined with generic scene types. Wielicki and Green¹⁷ note that: "The MLE-derived "cloud-cover" should be interpreted with caution. The MLE derived cloud cover will best approximate true cloud coverage for "average" cloud heights and optical depths. This is because the *a priori* data used by the MLE is an average over all observed cloud heights and optical depths." "The primary purpose of the MLE approach is to select the appropriate angular dependence model, [with] a crude measure of cloud amount generated as a by-product."

The optical properties of clouds, such as cloud fraction, cloud height, shape, optical depth, particle size and shape are major contributors to the anisotropy of the radiation. These cloud properties can vary rapidly in space and time.

At the least, LARI could follow the ERBE MLE/ADM system and obtain radiation budget data of similar quality, flying solo. In

fact, LARI already provides additional information compared to ERBE, namely, 6-10 broad spectral bands designed to provide crude information for separating major mechanisms which affect the total radiance. Thus we may separate, for example, the CO_2 contributions from a change in temperature. These data can be used in Global Circulation Models (GCMs) to produce forecasts which can then be critically evaluated.

Possible Additional Instrumentation

Let us now consider some choices for additional instrumentation capability to add to the LARI satellite. "Clouds are a key component of the global climate system, affecting [not only] the radiation balance, [but also] the hydrological cycle, and transport processes of the earth atmosphere. The most evident and significant daily weather events also involve clouds and precipitation. Lack of understanding of these effects on a global scale is widely regarded as the most important source of uncertainty in climate studies." "Because most clouds have sizes much smaller than those represented by global climate models, a significant part of the effort has been to develop ways of representing or parametrizing the effects of clouds on larger scales"¹⁸.

Thus, the key for both radiation budget studies, and for global climatology, is to provide a representation of clouds over the relevant pixel size. A number of programs are directed at collecting and interpreting data-sets for a global survey of cloud properties; these include the International Satellite Cloud Climatology Project and field projects including the First ISCCP Regional Experiment (FIRE), the Northwest Pacific Cloud Radiation Experiment (NWPCRE), the International Cirrus Experiment (ICE) and ERBE (see the review by Possow¹⁹ for further details). Studies of individual cloud dynamics may be better treated by ground-based and aircraft measurements, such as those proposed for the Atmospheric Radiation Measurements (ARM) program.

Many cloud properties can be obtained from multi-spectral images from aircraft or satellites.

While a number of such spectrometers have been designed and operated, we examine here the compact, light-weight Sandia National Laboratory Multispectral Pushbroom Imaging Radiometer (MPIR)²⁰. The full MPIR design provides data on these properties: cloud phase, particle size, height, coverage, temperature, emissivity, optical depth, aerosols as well as water vapor and surface albedo. The instantaneous field of view is 12 mrad for the 10.6 and 12 μm channels and 6 mrad for shorter wavelengths, which translates to a 4 - 8 km pixel size at nadir. These pixels are considerably smaller than the 20-30 km nadir pixel size of LARI, (and, for that matter, CERES and ERBE) allowing one to add contiguous MPIR samples for the ERB radiometer pixel average. MPIR will have excellent pre-launch and on-board calibration, with an absolute radiometric accuracy goal of $\leq 1\%$. Total weight is 25 kg, with requirements for 26 W of conditioned power and 30 W unconditioned power for a Stirling cycle cooler. The output data rate is 170 kbps, and nominal size is $8 \times 8 \times 14$ inches.

The combination of LARI (0.06 m^2 , 20 kg, 35 W) and MPIR (0.03 m^2 , 25 kg, 65 W) are likely to fit on a Pegasus launch, and together provide data on radiation budget, atmospheric constituents and clouds with excellent spatial complementarity.

We have considered the contributions provided by adding other instruments to the satellite, including LIDAR for cloud heights²¹, a camera for imaging and BRDF data, and microwave instruments to determine water vapor. The mission-oriented question is whether the incremental data significantly aids recovery of Earth radiation budget data, and whether such additions to the data are cost-effective. Our preliminary mission scenarios show that the combination of LARI and MPIR can be accommodated on a modest, flight-proven launch system such as Pegasus. Adding further instruments will increase the scope of the integration task, and will force the use of larger, perhaps less available launch systems. Significant benefits accrue from flying in the

same orbit as the DMSP satellites, which incorporate both microwave instruments and the Operational Line Scanner (an imaging instrument).

Constellation and Orbit Description.

In the following, we take a small satellite with the LARI and MPIR instruments as an illustrative example.

A frequently-used Earth radiation budget product is the monthly average over 2.5×2.5 degree regions. Actual data covers only a (sometimes small) subset of the desired full spatial and temporal coverage, necessitating filling in the "missing" pixels by interpolation and extrapolation. Part of the variability is unavoidable, due to changes in, for example, cloud cover. Obtaining full spatial and temporal coverage from satellites would require a large constellation, so one makes some compromises. A sun-synchronous orbit (~ 800 km, ~ 98 degrees inclination) permits a view of a given location twice per day at the same times, thus allowing repeated sampling for temporal averaging at specific locations. Two such satellites, properly phased, permit four views per day, and thus provide some diurnal sampling. (The NRC recommended three-hour revisit times, which would imply four satellites in polar orbits.) The supplementary orbit is one in the same altitude range with an inclination angle between 50 and 60 degrees. This permits sampling given locations at different times of day, from different angles and with different solar illumination, and increases the spatial coverage. Thus, three satellites simultaneously in the stated orbits provide the minimum set for global and diurnal coverage.

One can also tailor the orbits to improve access to particular sites, such as the Clouds and Radiation Testbed (CART) sites of the ARM program. One can choose polar orbits which have an integral number of periods per day, and which therefore revisit the same ground track every 24 hours. Such orbits permit measurements of specific sites from the same observation angle, and with the same solar zenith angle on a daily basis. (The

ascending and descending track revisits will be spaced by about twelve hours, and will each have its own repeating geometry for the measurements.)

Spacecraft Constraints.

The instruments imply several constraints on the satellite²². Both the LARI and MPIR require a three-axis stabilized platform, and both require nadir views with sufficient clear space to accommodate $\pm 60^\circ$ cross-track scanning. Pointing control is specified at ≤ 1 degree (3σ , each axis), while pointing knowledge is specified at ≤ 0.1 degrees (3σ , each axis). MPIR has a 300 rpm mechanical scanner, LARI has both a 15 rpm input optical scanner and a higher frequency chopper; these elements will cause some torques to be applied to the spacecraft from gyroscopic effects.

The power requirements for the instruments are relatively modest, with a total 61 Watts regulated and 30 Watts unregulated (cryogenic cooler) power. LARI detectors do not require cooling, and thermal control is relatively straight-forward.

The instrument digital processors will: monitor and control instrument operation and on-board calibration; acquire data, digitize, compress and store information; communicate with the satellite computer and send data to telemetry channels. Spacecraft processors and controllers will provide all other services.

The satellites are assumed to be launched at a rate of one per year with a three year design lifetime. The consumables will be sized for a five year operational lifetime. This will primarily affect the size of the solar panels (which is based on end-of-life performance) and the amount of fuel necessary for orbit maintenance.

The design of the spacecraft is taken to be constrained to the size, mass, and payload configuration capabilities of a small launch vehicle such as the Pegasus²³. The baseline version of the Pegasus has a payload volume of approximately 110 cm in diameter and 180 cm in length. The standard Pegasus with a hydrazine auxiliary propulsion system (HAPS)

can place 190 kg in a sun-synchronous orbit at 800 km. The same launch vehicle can place 220 kg in orbit at 800 km altitude at an inclination of 50 degrees.

A significant challenge for the spacecraft design is the need to record the LARI and MPIR instrument data which is continuously being generated at a rate of 205 kbit/s. This data rate results in 740 Mbit/hr, or 8.9 Gbit every 12 hours. There are several options for sending this amount of data to a central data processing and archiving facility. One option is to use a single dedicated ground station and download the data when the ground station is in view of the satellite. For an 800 km altitude, approximately 10 minutes of ground station connection time is available every twelve hours. Dumping 8.9 Mbit of data in 10 minutes requires a data transmission rate of almost 15 Mbit/s. The current state-of-the-art for small satellite telemetry systems is a 1 - 2 Mbit/s downlink data transmission rates, with reasonable extrapolations to 6 Mbit/s. A few dedicated ground stations would be required for this store-and-forward option to satisfy mission needs. In addition, approximately 10 Gbit of on-board storage per satellite would be needed.

A second option is to use TDRSS (Tracking and Data Relay Satellite System) to continuously relay and download the data to a high speed data link into the data processing and archiving facility. The TDRSS data channels can accept up to 5 Mbit/s continuously, which is significantly greater than the ~ 615 kbit/s data stream from three radiometric measuring satellites. However, using TDRSS requires that the transmitting satellite have a high gain antenna that can be pointed at the nearest (four are currently in operation) TDRSS satellite. Since the LARI / MPIR satellites will be nadir pointed and must maintain a fixed yaw-axis orientation with respect to the ground track to accommodate the cross track instrument scanning requirement, the transmitting antenna on the satellite would have to be gimbaled and steerable. This is a fairly expensive and

complicated addition to a small satellite.

The third telemetry option is to use a combination of store-and-forward and multiple ground stations. There are existing DoD and NASA distributed ground station systems that may have sufficient channel capacity. The system communication architecture to be used for these satellites, and the attendant data streams, will be designed after these options are evaluated.

Satellite Configuration

Figure 3 shows a candidate satellite configuration. The satellite is nadir-pointing with the LARI and MPIR instruments mounted on the bottom panel. Each instrument has the necessary ± 60 degree field of view cross-track and along-track. The size of the bottom panel on the satellite is limited by launch vehicle fairing constraints. The other required satellite subsystems are distributed throughout the satellite volume based on their mass properties and thermal management considerations.

The reaction control system (RCS) is used to provide thrust to adjust the orbit and satellite attitude, and to manage angular momentum on the satellite. The satellite RCS propellant requirements for orbit maintenance are minimal and can be met with monopropellant hydrazine (N_2H_4) thrusters or blowdown systems using pressurized nitrogen. If the satellite is designed as an integral part of the small launch vehicle, the upper stage launch functions, orbit insertion, and satellite initial orientation can be accomplished using a single RCS which will also provide orbit maintenance during the five year operational lifetime of the satellite. The configuration in Fig. 3 assumes that the satellite is delivered to, and inserted into, final orbit by an upper stage and the RCS functional capabilities are only for orbit maintenance.

The guidance, navigation, and control (GNC) subsystem provides determination and control of orbit and attitude and points the spacecraft. The three-axis attitude knowledge requirements are 0.1 degree (3σ , each axis) and the three axis attitude control requirements are one degree (3σ , each axis). Since there

are no major slewing requirements on the spacecraft, the attitude control system does not require a large bandwidth. At an altitude of 800 km, a three-axis magnetic torque rod and single, momentum-bias reaction wheel will provide adequate control authority and control bandwidth. The attitude determination will be accomplished by a combination of sun sensor, horizon sensor, and magnetometer. The RCS thrusters can be used to unload momentum from the single reaction wheel if required. Advances in technology allow for the inclusion of an on-board global positioning system (GPS) receiver which provides the satellite with continuous positional and time measurements.

The power system includes the solar panels, power control system, storage batteries, power regulation system, and satellite power bus. The solar panels are sized to sufficient peak power to supply the requirements of the payload and spacecraft bus, and still have enough excess capacity to charge the storage batteries. The capacity of the storage battery is driven by the need to record data continuously and the fact that the eclipse periods will be as long as 35 minutes out of the 100 minute orbit period. Body-mounting the solar panels on the sides of the satellite would complicate thermal management since the sun orientation is constantly changing. Hinging the solar panels at the top of the satellite body simplifies packaging in the launch vehicle and allows for a simple deployment mechanism. Since yaw control for solar panel power optimization is not possible, there is not a significant benefit to adding a rotating joint to the solar panels in order to control the orientation of the surface of the panel with respect to the sun.

The tracking, telemetry and command (TTTC) system performs the communication with the ground stations (or other satellites, if required). The command and data handling (CDH) system includes the spacecraft computer and controls the functioning of the spacecraft and auxiliary functions. The TTTC and CDH systems are integrated into a single electronics module.

The structure subsystem is comprised of the space frame and module mounting assemblies. The only mechanisms required are the solar panel deployment hinges, removable covers for the LARI and MPIR optic elements, and whatever interfaces are required with the upper stage of the launch vehicle.

Potential Launch Vehicles

Because of the small size and mass of these radiometric measurement satellites, there are several launch options. A Pegasus launch vehicle, which is dropped from the wing of a large aircraft, can place the satellite into any of the three orbits. The Pegasus is an especially attractive option in that it has some flight heritage, and allows considerable latitude in launch operations. The Taurus launch system, which is due for a first launch in late 1992, has more than sufficient payload capacity. Several other existing launch vehicles, such as Delta II, Titan series, and Ariane, are capable of placing these small satellites into any of the three orbits as partial payloads.

Data Management and Distribution

It would be a convenience to have a single ground station for control and data receipt, as is done at Los Alamos with the ALEXIS satellite. However, high speed ground links are being brought into operation at rates of 800 Mbits/s, which would require only tens of seconds transmission time per day to system nodes. Handling this volume of data would be rather straight-forward for a large integrated computing facility (ICF) such as exists at Los Alamos.

Data quality control, checking and integration are vital tasks. We plan to provide certain data to users in formats which are similar to those of ERBE, as well as enhanced data products, including, for example, spectrally resolved information. We note that it would be wasteful of national resources to duplicate the entire ERBE data analysis package, which amounts to some 250,000 lines of code, and we hope to integrate our data into the global change community as painlessly as is practicable.

Summary

The need for a continuous, accurate measurements of the Earth radiation budget is well-documented. The use of compact instruments on small satellites provides an opportunity to fill the gap in these data. We have described the Los Alamos Radiometric Instrument, which is capable of providing the necessary data in a timely fashion. We have described the benefits of flying LARI together with an appropriate compact spectrometer to enhance the analysis capability of the satellite package; the combination of LARI and, for example, the MPIR spectrometer can be launched on a Pegasus-class system. The use of several other potential additions to the payload was described: such further additions require the use of larger launch vehicles. Given the one- or two-instrument satellite, and the associated flexibility of launch opportunities, we envision launching the first satellite in three years, with annual launches thereafter to complete the constellation. Thus, the proposed instruments and satellites would make a very timely contribution to a problem of international concern.

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Fig. 1: Isometric view of the LARI instrument.

Fig. 3: Example of two-instrument payload integrated for Pegasus launch.

Fig. 2: Sample selection of contiguous wavelength bands.