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Low/medium density biomass, coastal and ocean carbon: a carbon cycle mission

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Abstract

As part of the Global Carbon Cycle research effort, an agency-wide planning initiative was organized between October 2000 and June 2001 by the NASA Goddard Space Flight Center at the behest of the Associate Administrator for Earth Science. The goal was to define future research and technology development activities needed for implementing a cohesive scientific observation plan. A timeline for development of missions necessary to acquire the selected new measurements was laid out, and included missions for low–medium density terrestrial biomass/coastal ocean, and global ocean carbon. This paper will begin with the scientific justification and measurement requirements for these specific activities, lightly touch on the options for having separate low Earth orbiting missions, and follow-up in more detail with a combined implementation study centered on a hyperspectral imager at geosynchronous altitudes, highlighting both its merits and challenges.

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1. Introduction

1.1. Why study carbon?

The major regulators of climate change are “internal”, including processes associated with the carbon cycle and photosynthesis. Warming of the Earth’s climate is driven primarily by the absorption of re-emitted solar energy by heat-absorbing “greenhouse” gases such as water vapor,

carbon dioxide and methane, and light-absorbing aerosols such as smoke and soot. Cooling on the other hand results from reflective clouds and other aerosols such as dust. Removal of greenhouse gases by the Earth’s terrestrial vegetation and its oceans by photosynthesis also acts to cool the Earth.

By examining the Earth’s carbon budget, the climate-carbon connection can be clearly seen. The annual increase in atmospheric CO₂ of about 3 Petagrams/year (Pg/y), results from the emission of nearly 7 Pg/y of carbon from the combustion of fossil fuels. However, roughly half of this fossil fuel emission is absorbed by the land (2 Pg/y) and oceans (2 Pg/y), resulting in a much slower increase in atmospheric

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carbon dioxide. Thus, these natural ecosystems provide a service to the global economy worth billions of dollars through natural mitigation of climate change. The reasons for this capacity of the Earth's land and oceans to absorb carbon dioxide are not adequately understood, and therefore future uptake cannot be estimated. Given the global importance of forecasting climate change, it is of utmost urgency to understand these processes.

1.2. Carbon cycle study

A team of scientists and engineers from the NASA Goddard Space Flight Center (GSFC), at the request of NASA Headquarters, led an inter-center and inter-agency planning activity for future studies of the sources, sinks, and transport of carbon in the atmosphere, on land, and in the oceans [1]. Working from the US Global Climate Change Research Program (USGCRP) Goals [2], the GSFC team and workshop participants examined the measurements and missions planned by the NASA Headquarters Earth Science Enterprise and identified critical gaps associated with carbon research. Three critical gaps were defined: (1) global time series of CO₂ atmosphere-surface exchange, (2) ecosystem carbon storage due to land biomass and its change as well as the carbon consequences of disturbance, and (3) measurements of critical biochemicals mediating global ocean surface layer uptake and export of carbon. The observations required to fill these gaps were also defined and include: (1) satellite-based observations of column and profile carbon dioxide concentration, (2) reprocessing of the historic land satellite record to track land use changes over time and quantify their carbon consequences, (3) satellite-based measurement of low/medium-density and high-density biomass, and (4) satellite measurement of chlorophyll and related organic and inorganic compounds in the coastal and upper deep ocean. A set of nominal missions designed to provide these measurements was developed and endorsed by the science team. Two of these missions are being introduced here, and will be cast first as individual low earth orbiting (LEO) implementations, and then as a combined Geosynchronous (GEO) mission. Information on the spectral consideration

underlying the measurement of carbon may be found in Ref. [3].

2. Science objectives and measurement requirements

2.1. Low-medium density terrestrial biomass & coastal ocean observations

The influence of climate change on terrestrial productivity can only be assessed with confidence when the dependence of processes underlying terrestrial carbon uptake, storage, and release on external influences is established, specifying how sink strengths will depend on climate variability, human actions, and other environmental forcings. Satellite observations provide the only practical means to obtain a synoptic view of the Earth's ecosystems along with their spatial distribution and temporal dynamics. Four areas where improved space-based measurements would significantly reduce uncertainties in the global carbon budget include: (1) land cover characterization at high spatial resolutions, (2) above-ground biomass estimates, (3) area estimates of disturbance and recovery, and (4) improved estimates of terrestrial and coastal ocean and estuarine productivity.

In terrestrial and coastal/estuarine systems, vegetation productivity cannot be directly determined from broad or select narrow (~20 nm) band space-based sensors currently available at LEO. In addition, the short-term down regulation in photosynthetic function due to environmental stresses cannot adequately be captured with current sensors, confounding attempts to interpret the biosphere's response to climate changes. A hyperspectral satellite sensor capable of *frequent* temporal observations is expected to provide this critical information. In the plan for developing new observations, we stress the need for: (1) developing spectral algorithms to directly assess terrestrial and estuarine productivity; (2) improving cataloguing of coastal wetlands and critical coastal land regions; (3) improving by at least an order of magnitude the error in the annual estimate of carbon storage in terrestrial biomass, with the overall goal of (4) linking terrestrial carbon cycle processes to climate variability.

Comprehensive, high spectral resolution observations in the visible, near infrared and middle infrared portions of the electromagnetic spectrum are required for investigations of the terrestrial biosphere, its variability, dynamics, and biogeochemical cycles.

2.2. Ocean carbon

The overall goal with ocean observations is to predict the variability of carbon (in its various forms) in the ocean, and thereby evaluate its role in climate change, and how that role might differ under various climate change scenarios. The productivity, or photosynthetic carbon flux, on the land and in the ocean are of about the same magnitude. However, the carbon biomass of the land is over two orders of magnitude higher than the ocean, which means the ocean achieves the same total photosynthetic fixation of CO₂ with a much smaller biomass. It is clear then, that the carbon cycle in terrestrial ecosystems is dominated by storage in biomass and strongly influenced by CO₂ losses due to respiration, whereas in the ocean it is highly correlated with the CO₂ and chlorophyll concentrations. Space-based observation strategies for the ocean therefore need to include measurements which can be used to estimate the flux of carbon, however indirect, across the air–sea interface and through the ocean's ecosystems.

In the oceans, the interaction between the solubility and biological pumps for CO₂ has never been established with the required spatial and temporal resolution, nor applied at global scales to determine their role in climate change. The proposed, future satellite-based observations are capable of filling this gap. In the plan for developing new observations, we stress the need for: (1) continuing and improving estimates of productivity, (2) expanding the emphasis on coastal ocean processes and specific regions of critical importance, (3) developing new remote sensing measurements for important but as of yet unobservable variables, and with the overall goal of (4) linking ocean carbon cycle processes to climate variability.

Comprehensive observations of the world's oceans in the ultraviolet, visible, and near infrared portions of the electromagnetic spectrum are required for investigations of the marine biosphere, its variability, dy-

namics, and biogeochemical cycles. Current systems at LEO under-sample data at mid and low latitudes due to cloud cover and infrequent passes (one pass every day or two).

3. Alignment of measurements with Earth science enterprise vision/strategic plan

Since the carbon cycle planning activity described in Section 1.2, the NASA Earth Science Enterprise (ESE) has formulated a number of science roadmaps on topics such as the water and energy cycle, weather and climate, chemistry and climate, and the carbon cycle as part of its strategic plan. The recommendations derived from the carbon cycle planning have been to a great degree incorporated into the carbon cycle roadmap. These plans include future missions for low density biomass/coastal ocean and global ocean carbon, as well as high-density terrestrial biomass (requires a totally different measurement approach). More recently, the ESE management has expressed interest in advanced measurement capabilities from geostationary altitudes, particularly hyperspectral measurements. As a result of these refinements in the ESE strategy, the GSFC group working on carbon cycle research and measurement technology has considered combining the low-density biomass/coastal ocean and the global ocean carbon concepts into a single geostationary instrument and mission concept which is described below.

4. Implementation options

Originally, two separate small-spacecraft LEO missions were conceived to support the observational requirements outlined above. The GSFC has been looking at the various scientific requirements and their interrelation. The outcome of this study has resulted in a combined implementation strategy that places the platform at GEO altitudes, but not without some challenges. Nonetheless, before discussing the combined mission, it is worthwhile to briefly present the individual mission options, as they represent a historical reference on which to base the new design. Instrument technical performance challenges existing for the LEO missions are only magnified by the sheer distance to

the target from the GEO vantage point. On the other hand, other operational aspects are simplified due to the constant or near-constant visibility of the spacecraft from selected ground stations.

4.1. Low-medium density terrestrial biomass and coastal ocean mission

A dedicated low-medium density terrestrial biomass and coastal ocean mission carrying an advanced hyperspectral imager would be able to meet the four measurement objectives outlined in Section 2.1. A number of technical and practical hurdles need to be overcome in order to implement a successful mission. From the technology side, the proposed hyperspectral imager would require much higher signal-to-noise ratios than those achieved for NASA's New Millennium Program Earth Orbiter 1 (EO-1) Hyperion instrument ($\text{SNR} \leq 50:1$). In addition, large area focal plane arrays, large capacity onboard data recorders, and high rate downlink communications systems are needed to improve mission performance.

The hyperspectral imager must cover a spectral range between 360 and 2350 nm, contain a short-wave infrared spectrometer element with a bandwidth of 10 nm, and a visible and near-infrared spectrometer with a bandwidth of 5 nm. An aircraft instrument is also needed for algorithm development and validation.

Several candidate low-cost, three-axis stabilized spacecraft were identified that met instrument requirements with margin. However, some modification to the standard spacecraft command and data handling (CDH) and communications subsystems is anticipated in order to accommodate the inherently high data rates associated with hyperspectral sensing. A propulsion system was also included in the configuration to allow for orbit maintenance and for possible formation flying with other land-imaging platforms. A 705 km sun-synchronous orbit with a 10:30 am descending node was the orbit of choice, to continue the heritage of the Landsat and Terra/Aqua platforms. A mission life of five years was chosen in order to provide a period of time sufficient for monitoring terrestrial productivity and biomass changes. Fig. 1 shows the conceptual spacecraft layout developed for this mission.

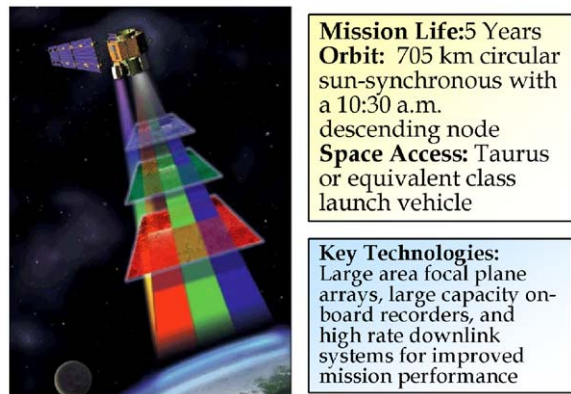


Fig. 1. LEO option, low-medium density biomass & coastal ocean mission.

4.2. Ocean carbon mission

The original concept for an ocean carbon mission included a small, low-cost, three-axis stabilized spacecraft, carrying on board a single multi-spectral imager. In situ measurements from ships and optical buoys provide additional calibration and validation data for comparison with space-borne instrumentation. Irradiance measurements in 10 spectral bands, from the ultraviolet to the near infrared, would be acquired by a rotating, scanning telescope equipped with an on-board solar calibrator. After launch by a Pegasus XL or equivalent launch vehicle, an on-board propulsion system is employed for orbit raising and for orbit maintenance. A 705 km polar, sun-synchronous orbit with a 12:00 noon crossing time is ideal. For planning purposes, a 5-year mission lifetime was assumed. One design would be an improved SeaWiFS with additional bands for fluorescence line height and UV absorption. Specific technologies are sought that improve the precision, accuracy, range, and reliability of ground-based validation measurements as well as the aircraft and space missions they support. The miniaturization of drifter buoys with optical, pCO_2 , and nutrient sensors is one such improvement that has already been identified. Fig. 2 shows the original spacecraft conceptual layout.

4.3. Combined mission concept

A combined mission design can address the scientific requirements embodied in the original mission

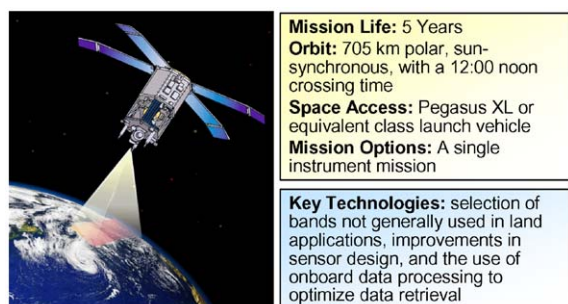


Fig. 2. LEO option, ocean carbon mission.

concepts, while at the same time increasing the scientific return of a single spacecraft. Notwithstanding, the technical challenges embodied by one mission are now shared among both sets of measurement objectives. Compromises reached in one area can affect the performance and scientific yield in another. In general terms, the land requirements for spectral coverage/resolution and signal-to-noise ratios (SNR) are more extensive than those imposed by the oceans counterpart. The key in achieving a successful marriage of both missions lays in the ability to achieve the desired measurements without compromising science below performance thresholds.

5. Low/medium density biomass, coastal and ocean carbon: an integrated approach to measurements

The previous sections expanded on the scientific rationale of individual missions, and lightly touched on the pragmatic benefits that can be extracted from integrating measurements into one implementation approach. In what follows, we present the details of how this combined mission may be achieved, and what problems may be encountered along the way.

5.1. Orbit design options, and operations phases

A number of geosynchronous-altitude orbit options have been considered, with varying energy requirements. The operational concept is divided into two main phases: a geosynchronous/geostationary phase (Phase I) centered at 95-degrees West longitude covering North and South America, and a global-coverage

phase (Phase II), where the ground track repeats itself once every 7 days. Each phase would be expected to last 2 years. The resulting options and Delta-V requirements are summarized in Table 1.

A fixed inclination of 28.5 degrees for both mission phases not only results in the smallest Delta-V requirements, but its “figure-8” ground-track allows for improved coverage at higher North-South latitudes. Hence, case 2 is chosen as the best compromise for latitudinal coverage, global coverage, and fuel needs, and is the basis for the rest of the analysis included here. Case 2 ground track is shown in Fig. 3 for both mission phases (a and b).

A geosynchronous platform lends a unique vantage point from which to observe Earth phenomena at high temporal resolutions. It also presents a significant challenge in trying to achieve high enough spatial resolutions and signal-to-noise ratios, both of which are competing goals. Indeed, this problem is compounded by the large distance between sensor and target. The instrument design must contend with these challenges, and will be discussed next.

5.2. Instrument concept

A number of instrument choices are being considered as candidate payloads for this design study. They include modified versions of: (1) NASAs EO-1s Hyperion hyperspectral imager; (2) the Italian HypSEO hyperspectral instrument; and (3) a NASA Instrument Incubator Program (IIP) derived hyperspectral instrument. The key words in the previous sentence are “modified” and “hyperspectral”. In reality there is still no design for a hyperspectral imager at GEO altitudes with the required performance.

The Low Earth Orbiting concepts are similar in that they utilize a telescope oriented towards nadir, a slit grating or other spectrally dispersive optical elements to spread the image in the spectral direction, and CCD or Photodiode Array type detectors. The spatial axis is aligned perpendicular to the direction of flight, while the spectral axis is parallel to the direction of flight. The instrument scans the scene at the orbital velocity. These types of remote sensing instruments have several advantages such as proximity to the scene, and simplicity due to the use of orbital motion to accomplish the scan. Several drawbacks are inherent to this form of instrument. They can only take data once a day

Table 1
Orbit choices and required onboard delta-V (Launch from ETR)

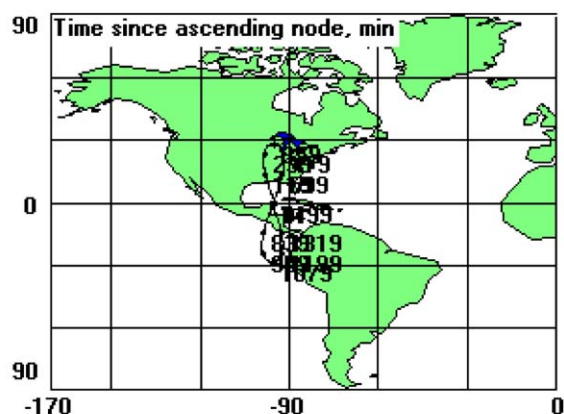
| | Delta-V (km/s) | Circular orbit geocentric radius (km) | Maneuver | Ground track |
|----------|-------------------|--|--|---|
| Case 1 | | | | |
| Phase I | 1.8 | 42160 | Circularization & Plane Change from GTO. $i = 0$ deg | Equatorial, fixed at 95-deg W long. |
| Phase II | 1.7 | 38573 | Drop down to lower orbit, $i = 28.5$ deg | Figure 8, with Eastward walk once every 7 days |
| Total | 3.5 | | | |
| Case 2 | | | | |
| Phase I | 1.5 | 42160 | Circularization from GTO. $i = 28.5$ deg | Figure 8, with center fixed at 95-deg W long. |
| Phase II | 0.14 | 38573 | Drop down to lower orbit, $i = 28.5$ deg | Figure 8, with Eastward walk once every 7 days |
| Total | 1.64 | | | |
| Case 3 | | | | |
| Phase I | 1.8 | 42160 | Circularization & Plane Change from GTO. $i = 0$ deg | Equatorial, fixed at 95-deg W long. |
| Phase II | 0.14 | 38573 | Drop down to lower orbit, $i = 0$ deg | Equatorial with Eastward walk once every 7 days |
| Total | 1.94 | | | |

for sunlit and reflected solar IR channels, at the same relative sun angle. The integration time is determined by the spatial and spectral resolution. For high ground resolution images, scene contiguity may not be possible near the equator, and at any rate, adjoining swaths will be sampled approximately 90–100 min apart.

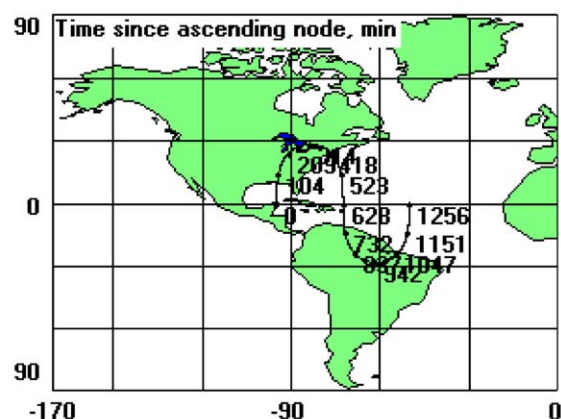
A hyperspectral imager positioned at geosynchronous orbit also has several advantages and disadvantages. The large distance from the earth requires a much larger aperture for diffraction limited resolution, and for the collection of light. The solid angle projected from GEO to the desired resolution on the ground is very much smaller than from LEO. The necessity of a scanning mechanism also complicates the GEO instrument. The advantages though are substantial. Full diurnal and spatial coverage is possible, albeit only for the areas within view of the satellite.

The addition of a scan mechanism also enables a variable integration time, so that higher signal-to-noise measurements may be made in certain areas, while other areas may be scanned quicker if the signal to noise accuracy is not warranted.

A preliminary study was performed to evaluate a geosynchronous hyperspectral imager. The optical layout was similar to the low Earth orbit imagers, but obviously scaled up to accommodate the greater distance. The aperture required for diffraction limited performance at GEO for 100 m resolution was 1.2 m. An elliptical flat scan mirror with a minor axis of 1.2 m was placed at the entrance pupil of the telescope. The telescope output was field stopped with a slit at the focal plane. The resulting beam was spectrally split, with a 340–1000 nm portion sent one way, and a 1000–2400 nm portion sent another. Both optical



(a)



(b)

Fig. 3. Chosen mission ground tracks provide hemispheric and global coverage during two mission phases. (a) Geosynchronous Orbit, 28.5-degree inclination. (b) 7-day ground track repeat rate (1-day Eastward Motion shown).

paths included a grating to spectrally spread the resulting scene. It was assumed that silicon CCDs or Photodiode arrays would be used for the visible and near infrared channels, and Mercury Cadmium Telluride detectors used for the Short Wave Infrared Channels. The instrument would then scan the scene perpendicular to the spatial direction, and parallel to the spectral direction on the detector.

The volume of an instrument like this would be approximately 1.3 m by 1.3 m \times 2.5 m. It would weigh approximately 1000 kg, with adequate contingency. Power required was estimated to be 350 W, including thermal control.

When this instrument was evaluated for signal to noise performance, values such as 100 m resolution, 1 nm spectral channels, and full disk coverage every 2 h still resulted in single digit signal to noise figures. The irradiance of the scene, coupled with the small size and great distance of the scene, and narrow spectral channel width resulted in very low levels of light reaching the detectors. When the instrument was analyzed with wider channels, longer integration times and lower resolution, more reasonable signal-to-noise figures resulted. Table 2 details the results of this analysis. A 4-degree per minute scan rate results in one full Earth-scan every 3 h, and clearly a 1-degree per minute rate translates into about 1/4th of this area.

The results of this study show that full diurnal coverage of portions of the earth are possible utilizing large aperture remote sensing instruments. The large distance from the telescope to the scene limits resolution, spectral channel width, and temporal resolution. Several 2.4-m aperture cases were analyzed to demonstrate the scale required to achieve 1000:1 signal-to-noise in geosynchronous orbit. The volume, mass, and power for this configuration were not estimated.

In general, land observations have more stringent spatial resolution and spectral requirements than the ocean carbon measurements. It is then reasonable to assume that a combined mission with at least a hyperspectral instrument satisfying the performance requirements of the former suffices to accomplish the overall science objectives. Nonetheless, this generalization is shown to break down in specific cases, as optimizing the instrument (and mission) design to land measurements may not necessarily result in a favorable condition for ocean measurements.

Table 2 highlights one important instance where this is the case (bold type rows): a relatively adequate SNR implementation for land measurements is not so acceptable for ocean measurements; the discriminating factor being the order of magnitude difference in irradiance between land and ocean scenes (green light). In reality, both land and ocean measurements require a SNR of about 1000:1, a condition difficult to achieve as evidenced by this study. In order to constrain the problem however, the aperture was fixed at 1.2 m, and the spacecraft was sized given this assumption. This would at least represent a lower boundary on which to base more ambitious designs.

Table 2
SNR performance changes as a function of instrument parameters

| Resolution (m) | Aperture size (cm) | Bandwidth (nm) | Scan rate (deg/min) | Typical SNR |
|---|--------------------|----------------|---------------------|-------------|
| LAND: spectral radiance of 30 W/(m ² micron sr), 562 nm center | | | | |
| 250 | 120 | 5 | 4 | 186 |
| 250 | 120 | 5 | 1 | 385 |
| 250 | 120 | 10 | 1 | 548 |
| 500 | 120 | 5 | 4 | 548 |
| 500 | 120 | 5 | 1 | 1097 |
| 500 | 240 | 5 | 4 | 1097 |
| OCEAN: spectral radiance of 3.8 W/(m ² micron sr), 551 nm center | | | | |
| 250 | 120 | 5 | 4 | 63 |
| 250 | 120 | 5 | 1 | 125 |
| 250 | 120 | 10 | 1 | 177 |
| 500 | 120 | 10 | 1 | 528 |

Table 3
Spacecraft mass and power budgets

| Element | Mass (Kg) | Power (W) | Performance note |
|--|-----------|-----------|----------------------|
| Hyperspectral imager | 1000 | 455 | |
| Core bus | 548 | 439 | |
| Propulsion system | | | |
| Stage 1 Apogee Kick Motor (solid) | 2218 | | |
| Stage 2 N ₂ H ₄ Mono-Prop System | 497 | | |
| Power system | | | |
| NiH ₂ battery | 17 | | 18.5 Ah |
| Solar arrays (2) | 60 | 935 (EOL) | 8.5 m ² |
| Totals | 4340 | 894 | |
| Delta IV-M+ (4,2) performance | 5666 | | <i>i</i> = 28.5 deg. |
| Launch vehicle margin | 23% | | |
| Atlas V 401 (SEC) | 5950 | | |
| Launch vehicle margin | 27% | | |

SEC=single engine centaur

5.3. Spacecraft accommodation

The Rapid Spacecraft Development Office (RSDO) at the NASA GSFC has a catalogue of spacecraft that may be used for a variety of missions, mainly in LEO. Most of these are small spacecraft that can be modified to incorporate specific requirements. Given current instrument mass and power estimates however, only a couple of larger candidates may be useable, but not

without some important modifications. The following spacecraft specification is therefore largely based on a dedicated design, and only loosely based on the Spectrum Astro SA-200HP, and Orbital's MidStar.

A summary of spacecraft mass and power budgets are shown in Table 3. The total spacecraft wet mass including the apogee kick motor (used for circularization to GEO) is about 4340 kg. This can hardly be called a "small spacecraft", except that the bus without

the propulsion system weights about 625 kg. The relatively large instrument mass and the resulting propulsion system required to place the payload into a GEO orbit are the reason the total mass results accumulates into a medium-sized spacecraft.

An instrument data rate of about 8 Mbits/s (Mbps) results from the following assumptions: 1 K×1 K image pixel array, 250-m resolution, full-disk scan once every 3 h, housekeeping, data pre-processing, and 3:1 lossless data compression scheme. Other schemes considered could cause this rate to vary, anywhere from 2 to 8 Mbps. To hold 3 h worth of data, the on-board recorder must be able store at least 86.4 Gbits of data. Downlink communications at 80 Mbps (X-Band) is able to dump stored data in about 18 min. Given that data is only acquired during daylight hours, a maximum of 12 h of operations is required. This means that there needs to be at least four downlink windows per day, and a data storage buffer capable of supporting 18 min of data acquisition during downlink times. The resulting total recorder capacity must then be about 95 Gbits. Finally, a Space Wire (1355) data bus is capable of supporting the expected 8 Mbps data rate, with considerable margin.

The propulsion system is sized based on blowdown hydrazine monopropellant, with a specific impulse of 230 s. It holds enough fuel for orbital maneuvers and station-keeping for a 4-year orbital mission, with contingency. A solid propellant motor is used as the apogee kick stage, for circularization from Geo-Transfer Orbit (GTO). A STAR 31 or equivalent motor may be used to this effect. The power system is sized based on NiH₂ batteries, and triple-junction GaInP/GaAs/Ge cells. Table 4 summarizes the spacecraft performance.

5.4. Launch vehicle options

An injected payload mass of 4340 kg requires either a Delta IV or Atlas V expendable launch vehicle. A Delta IV Medium with 4-m fairing and two strap-on solid motors can take the spacecraft to GTO orbit, with 23% performance margin. Equivalently, an Atlas V 401, with a single engine Centaur stage yields a 27% launch vehicle performance margin. Fig. 4 shows the budgeted vehicle size inside the static envelope of an Atlas V Large Payload Fairing (LPF). As can be seen, there is ample room for the spacecraft to grow

Table 4
Spacecraft performance summary

| General performance parameters | |
|--|-------------------|
| Payload envelope (m) | 1.3 × 1.3 × 2.5 |
| Payload mass (kg) | 1000 |
| Average power—EOL (W) | 935 |
| Bus voltage (V DC) | 27.5–33 |
| Battery (A h, nickel–hydrogen) | 18.5 |
| Solar array | GaInP/GaAs/Ge |
| Payload thermal restrictions | None |
| Launch vehicle (Current) | Delta IV, Atlas V |
| Lifetime reliability (4-year Mission) | 0.9 |
| Command & data handling | |
| Processor | 32 bit RISC |
| Telemetry & command storage (Gbits) | 95 |
| Data bus | Space wire (1355) |
| Downlink rate (Mbps, X-Band) | 80 |
| Telecommunications protocol | CCSDS |
| Autonomy | Enabled |
| Guidance, navigation & attitude control | |
| Control strategy inertial and Nadir pointing | 3-axis stabilized |
| Attitude knowledge (arcsec) | 0.4 |
| Attitude control (arcsec) | 1.4 |
| Stability (arcsec/s) | 0.1 |
| Independent safhold processor | Implemented |
| Maximum slew rate (degree/min) | 6 |
| Structure | |
| Hexagonal structure | Aluminum |
| Instrument interface | +Z Deck |
| Launch vehicle interface | –Z Deck |

in size, but within the 27% mass margin. The situation is similar for a Delta IV option.

6. Conclusions

This preliminary study demonstrates both the advantages and challenges of a GEO hyperspectral platform. Combined measurements of low/medium density biomass and ocean carbon are possible and highly desirable. Advantages are full diurnal hemispheric coverage of the Earth, or near-global coverage at a minimum rate of once every 2 days, all achiev-

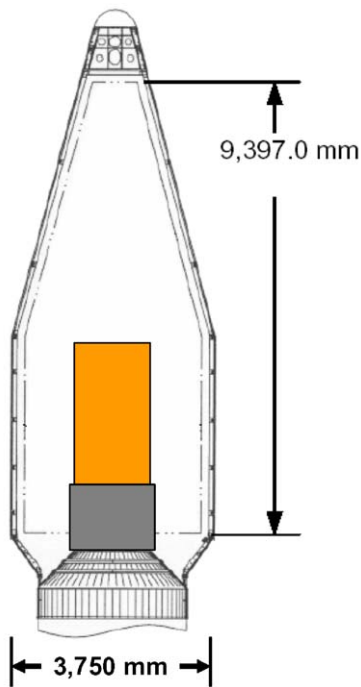


Fig. 4. Static envelope for the Atlas V 400 series, 4-m LPF.

able with a single spacecraft. The challenge still remains to obtain desired high resolution, high SNR hyperspectral images. Although the telescope aperture was sized at 1.2-m for 100-m diffraction-limited resolution, acceptable SNR can only be achieved

at effective resolutions nearing 250-m and greater. This becomes more problematic for scenes with low irradiance values, such as the open ocean, and less so for land observations. Large-scale optics and advanced detectors are among two of the technologies that need further exploration and development. Notwithstanding, a more detailed analysis is needed in order to bring about alternative solutions not considered during this initial feasibility study.

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