



# Vesta

A fundamental mission for the more accurate understanding of climate change

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## Abstract

Climate change is a major environmental issue of the early 21<sup>st</sup> century. It is determined by many climate forcings one of which is the rise in the concentration of the greenhouse gases (GHG) in the Earth's atmosphere, the most radiatively forcing gas being CO<sub>2</sub>. A wide range of direct and indirect measurements confirm that the atmospheric mixing ratio of CO<sub>2</sub> has increased globally by about 100 ppm (36%) over the last 250 years<sup>1</sup>. Current estimates indicate that in relation to CO<sub>2</sub> released from all sources of burning, global emissions from biomass burning produce 26% of the net CO<sub>2</sub> emissions annually<sup>2</sup>. A pressing scientific challenge in this respect is a more accurate understanding of the existing uncertainties in the processes within the carbon cycle and making more accurate predictions for future estimates of how the cycle will function. This crucial task could be performed by the dedicated Vesta mission, Vesta is proposed to derive data on CO<sub>2</sub> emissions through measurements of the Fire Radiative Power (FRP) of biomass burning (anthropogenic & wildfire) in the region of the tropics where 80% of the global CO<sub>2</sub> emissions of biomass burning come from<sup>3</sup>. This will be done through the use of new combinations of spatial and temporal measurements with a four channel spectral sensor that no previous satellite provided and no current satellite provides. There is currently no active or planned mission aside from Vesta dedicated solely to the objective mentioned above.

## 1. Scientific Background

There are many factors which shape climate, the carbon cycle, the interchange of carbon between the atmosphere, oceans, and land surface is one of the most important cycles of the earth. The capacity of the carbon sinks to continue to absorb CO<sub>2</sub> emissions as they currently do is a topic of great interest in the scientific community where there is a fundamental need for more accurate estimations of how the cycle functions, in order to predict how it will continue to function.

Carbon dioxide is responsible for 63% of the radiative forcing of all of the GHG's<sup>4</sup> and as its concentration continues to increase, a greater amount of radiation from the sun becomes trapped in the atmosphere which further warms the planet. It should be mentioned that water vapour is the most abundant greenhouse gas but it is generally considered as a response of the system rather than a climate forcing in its self.

A major contributor to CO<sub>2</sub> emissions is biomass burning, (all types of anthropogenic & wildfire). Biomass burning contributes as much as 40% of the gross (fire/fire + fossil) and 26% of the net (including re-growth of savannas') carbon dioxide emissions globally<sup>2</sup>. The amount of biomass emissions has been dramatically increasing over the last 40 years due to the increasing tropical deforestation.

## 2. Scientific Case

### 2.1 Main objective

Vesta is a mission designed to derive data on CO<sub>2</sub> emissions through measurements of the Fire Radiative Power (FRP) of all types of biomass burning (anthropogenic & wildfire) in the region of the tropics where 80% of the annual global CO<sub>2</sub> emissions of biomass burning come from<sup>3</sup>. This will be done through the use of new and finer combinations of spatial and temporal measurements that no previous satellite provided, no current satellite provides and no other future satellite has been designed to provide. The data on CO<sub>2</sub> emissions is intended for improvements in the accuracy of the estimates of global CO<sub>2</sub> emissions, the carbon cycle and ultimately to further develop an understanding of global climate change.

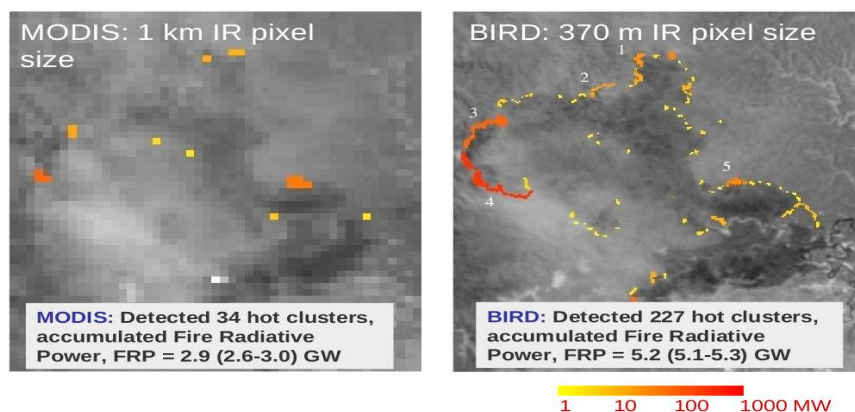
The first major justification behind the Vesta mission objective to focus on biomass burning is that the annual global CO<sub>2</sub> emissions of 40% (gross) are from biomass burning. However the net CO<sub>2</sub> emissions is actually 26%, this is because some types of biomass like savanna take up most of the carbon they have released within a short period of time, making the overall change nearly zero<sup>2</sup>. However the gross emission of 40% also contains aerosols which once released into the atmosphere stay there.

The second scientific justification is based on the knowledge that the geostationary sensors like GOES-E/W and SEVIRI provide necessary temporal coverage of biomass burning in low latitudes but lack sufficient spatial coverage. The MODIS instrument currently in use on the polar orbiting satellite Terra and the Sentinel-3 mission due to launch in 2013 provide sufficient spatial resolution but not temporal resolution.

**Table 1: Major satellite missions for deriving FRP (source: B. Zhukov, D. Escorial)**

Mission	Sensors	Coverage		Resolution	
		Spatial	Temporal	Spatial	Temporal
<b>GOES</b>	GOES - E/W	N/S America	1995 - present	4 km	30 min
<b>TERRA</b>	MODIS	Global	2001 - present	1 km	1 day
<b>METEOSAT</b>	SEVIRI	Africa, Europe	2006 - present	4.5 km	15 min
<b>Sentinel 3</b>	SLSTR	Global	2012 - 2035	1 km	daily
<b>Bird</b>	HSR	Global	2001 - 2006	370 m	
<b>TRMM</b>	VIRS	Tropical Region	1997 - 2011	2.5 km	92.5 km
<b>VESTA</b>	VESTA - MIR/TIR	Tropical Region	2020 - 2027	230 m	1.5 - 4 hours

BIRD was the only mission that was able to provide the necessary spatial resolution, hence the adequate determination of FRP and CO<sub>2</sub> emissions. The Vesta mission has a sensor which is able to give even better images that BIRD could, due to Vesta’s better spatial resolution.



**Figure 1: B.Zhukov et al. Comparison of fire detection & quantitative characterisation by MODIS & BIRD**

Figure 1 shows the difference in the images produced by MODIS and bird of the same fire. It is very clear that in order to gather more accurate data on FRP of biomass burning there is a need for a satellite mission which can cover both the spatial resolution and temporal coverage needed to do this. This is what the Vesta mission is providing.

## 2.2. Secondary Objectives

- Assessment of aerosol emissions through combination of FRP measurements with the determination of effective fire temperature.



- Coverage of land use change through determination of the Normalised Difference Vegetative Index (NDVI).

### 3. Methodology

To measure fires from space, we take advantage of the water vapour absorption gap between 0.4-15  $\mu\text{m}$ . The FRP is measured with the MIR and TIR channels (resp. 3-4  $\mu\text{m}$  and 10  $\mu\text{m}$ ). MIR permits the retrieval of the flame temperature and the hot solid part below the flame is obtained by the TIR. The NIR channel at 0.85  $\mu\text{m}$  with higher spatial resolution enables co-registration of sub-pixel fire. The temperature of the fire is deduced from the FRP. When the temperature is higher than 850 K a complete oxidation of the fuel takes place, in contrast to lower temperatures where trace gases like CO, CH<sub>4</sub> and soot particles are produced. The quantity of the gas emitted is proportional to the FRP, which is linearly related to the combustion rate. The VIS and NIR channel allow the calculation of the NDVI, by comparing the ratio of the difference between the channels against the sum of the reflectance of the VIS and NIR channels. Moreover, the limitations in FRP measurements due to cloud flagging is known and can be identified by the NIR channel. [The FRP is derived from the fire emitted spectral radiance, which is calculated as the difference between the MIR spectral radiance of the active fire pixel and that of surrounding non-fire background pixels].

#### 3.1 Scientific Requirements

To utilise FRP for more accurate measurements of CO<sub>2</sub> emissions from biomass burning, the key lies in finding an optimal setup of spatial, temporal and intensity resolution, as well as an optimal coverage and an ideal life time for the mission. Lots of fires down to 500 m<sup>2</sup> are missed due to low detection resolution in the VIS/NIR detector range (of current missions mentioned above). Unfortunately, small fires occur much more often than large fires and therefore increasing the uncertainty of CO<sub>2</sub> emissions due to biomass burning<sup>5</sup>. To increase the amount of smaller fire detections a spatial resolution of 120 m (500 m<sup>2</sup> with sub-pixel detection) for the VIS/NIR sensor is required, as demonstrated by the pilot mission BIRD which detected three to six times as many fires than MODIS for the regions under investigation<sup>6</sup>. Secondly, to reach an accuracy for the FRP of 0.2 MW, a spatial resolution for the MIR/TIR less than 300 m is needed for fires down to 500 m<sup>2</sup> with sub-pixel detection. A geo-localization of less than 1 km guarantees a validation of the FRP products of the geo-stationary satellites.

The vast majority of gas emission (>99 %) due to fires which take place within 4-8 h after ignition. That is why a high temporal resolution of 4 h down to 1.5 h is required<sup>7</sup>. Moreover a high revisit time of the fire permits the monitoring of the different fire phases and dynamics and therefore the different gas and aerosol productions<sup>7</sup>. The temperature of fires is between 650 K and 1375 K but as we measure the background radiance as well a temperature range down to 280 K is needed. For detection of small fire (500m<sup>2</sup>) radiation and even to give more accuracy on the brightness temperature and thus on the burned biomass, a sensitivity of less than 10 K is required. As the mission covers between  $\pm 25^\circ$  (80% of CO<sub>2</sub> from biomass burning) and is additionally poorly observed we limit the latitude coverage in between this range. At latitudes past 25° there is vastly less CO<sub>2</sub> emissions, at  $\pm 50^\circ$  the amount of CO<sub>2</sub> from biomass burning is only 87% (a 7% difference). The duration of the mission should at least cover an El Nino-Southern Oscillation (ENSO) (4-7 y) to observe the influence of this effect on CO<sub>2</sub> biomass burning and hence FRP.

### 4. System Design

#### 4.1 Payload

For our mission we decided to use four spectral channels [Table 2]. The MIR Channel is the most appropriate one to detect fires and TIR channel is needed to catch false alarms due to warm surfaces and to improve the detection of fires in the presence of smoke and clouds. VIS and NIR channels will be used to reduce the number of false detections due to sun glint<sup>8</sup>. Additionally the two channels can be combined for the NDVI which allows detection of unseen burned areas. The VIS/NIR sensor is based on the WAOSS-B concept<sup>9</sup>. The main advancements of the sensor is a new optic, an 8192 CCD and an optimized sensor electronic (transfer the data compression to the satellites on-

board computer). The new optic is needed to get a larger swath and therefore a better temporal resolution; the bigger CCD increases the spatial resolution while keeping the large swath. To optimize the sensor electronics it is useful to reduce the power consumption and weight.

The MIR/TIR sensor design is the proven HSRS concept, flown on bird and chosen as the basis for the FUEGO sensor will be adapted. To fulfill the systems requirements it needs higher spatial and temporal resolution. We need 4 TIR and 4 MIR sensors to reduce the power consumption and weight we will combine the sensors.

Table 2: Sensor specifications

	4x MIR/TIR Sensors	WAOSS-B Heritage
<b>Channels</b>	MIR: 3.45 – 4.15 $\mu$ m TIR: 10.0 – 12.0 $\mu$ m	VIS: 0.60-0.67 $\mu$ m NIR: 0.84-0.90 $\mu$ m
<b>Focal length</b>	57.39mm	21.65mm
<b>f number</b>	2.0	2.8
<b>Pixel number</b>	2 x 512 (staggered)	8192
<b>Pitch</b>	30 $\mu$ m	6.5 $\mu$ m
<b>Thermal resolution</b>	0.2/0.5 NEDT	500W/(m <sup>2</sup> $\mu$ msr)
<b>FOV</b>	15.245°	60.979°
<b>Swath width</b>	~235.5 km	942 km
<b>Footprint at nadir</b>	~ 230m x 230m	115m x 115m

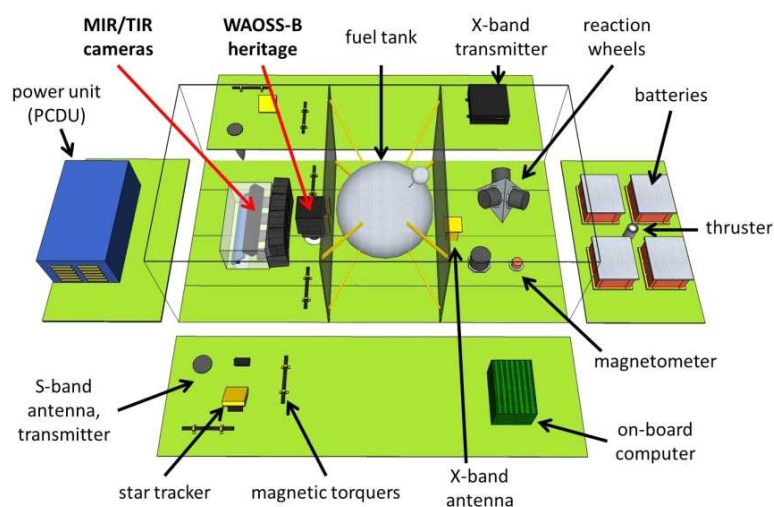


Figure 2 Internal instruments of the sensor

### Calibration

The calibration for the cameras uses one reference point for MIR and TIR channels obtained by means of an IR blackbody at a temperature floating with the environment. For the second reference point, the temperature of the blackbody can be set to a particular value. The black body is observed by pointing the mirror.

Calibration of VIS channel is made through "dark" view and vicarious calibration. The dark reference is obtained by means of a shutter, while the high reference point can be exploited from the observation of other existing external sources, like the ground surface and the moon.

## 4.2 Orbit Architecture

The Walker constellation was identified to be the best choice to satisfy the requirement of short revisit times at low latitudes between  $\pm 25^\circ$ <sup>11</sup>. A trade space analysis regarding the three parameters, altitude, number of orbit planes and number of satellites per orbital plane was performed. From a total of 81 possible constellations, three options, shown in Table 3 were chosen as the best candidates satisfying the given requirements and featuring reasonable numbers of satellites. The basis of the prize estimations will be explained hereafter.

Table 3: Options for constellations

Option	No. Planes	No. sats/plane	No. launches	Mean revisit time (h)	Max revisit time (h)	Estimated cost (M€)
1	2	2	2	3.3	7.9	532
2	2	3	2	1.9	5.0	632
3	3	3	3	1.6	4.5	825

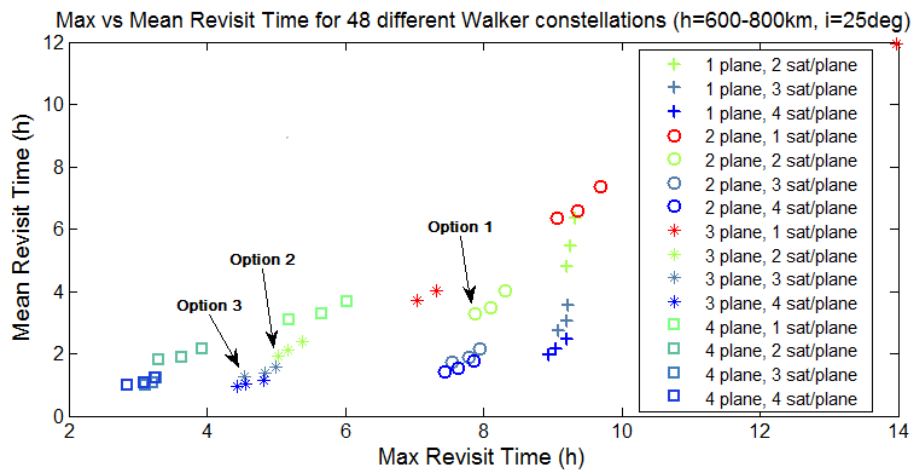


Figure 3 Trade space analysis of walker orbit constellations (48 out of 81 shown)

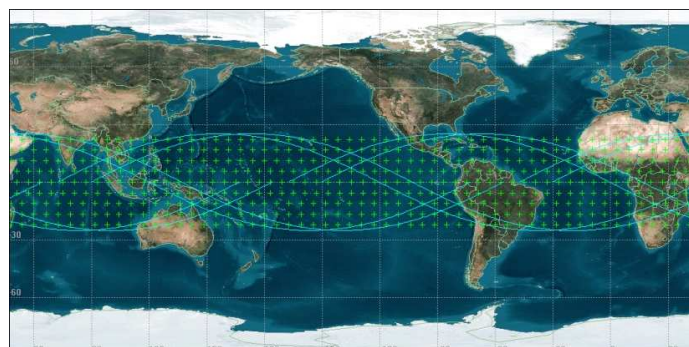


Figure 4 Walker constellation with 3 orbital planes & 2 satellites per plane, covering the area between latitudes  $\pm 25^\circ$  (option 2)

### Propulsion for Orbit

The  $\Delta v$  requirement for each Vesta satellite is comprised by the need of orbit insertion that is the positioning within the orbital plane after ejection from the launch vehicle relative to the constellation, de-orbiting capability and orbit



maintenance throughout the mission duration. The former is accomplished by Hohmann transfers, changing the altitude by the magnitude in the order of 10km, and utilizing different angular rates for different orbit heights, guaranteeing reasonable overall maneuver times below 20 days. An overall of  $\Delta v=10\text{m/s}$  is calculated for the maneuver and return.

In addition, the propulsion system is designed to perform an orbit change regarding the Right Ascension of the Ascending Node (RAAN), enabling the distribution of six satellites on three orbital planes by two launches only, and leading to a major cost reduction. This maneuver is accomplished by altitude change in the order of 100-200km off the nominal altitude. The satellites on different orbit heights then experience a difference in perturbations caused by the oblateness of the Earth (commonly referred to as  $J_2$  Perturbation)<sup>11</sup>. This way, the change in RAAN necessary to transform a 6/2-Walker constellation into a 6/3-Walker constellation can be performed with a drift time in the order of 6-7 months. The total  $\Delta v$  budget for orbit insertion, maintenance and de-orbiting within 25 years was calculated with 15% margin to be 110.5m/s. For Option 2, the required  $\Delta v$  accounts for  $\Delta v=267.7\text{m/s}$  including margin.

### 4.3 Spacecraft Design

#### Communications System

Ground Stations: Two Ground Stations (GS) are selected from the ESA Tracking Network (ESTRACK) to keep low operational cost : Kourou (5.251°N, 52.80°W) as a main station and Dongara (29.2°S, 114.9°E). The use of a second GS is to distribute the data download and as a backup solution in case of failure of the Kourou stations. The characteristics of the ESTRACK GS are summarized in the following table:

Table 4: ESTRACK GS characteristics

	Uplink	Downlink
<b>Antenna Dish Diameter</b>	15 m	15 m
<b>S-Band Frequency (MHz)</b>	2025-2120	2200-2300
<b>X-Band Frequency (MHz)</b>	7145-7235	8400-8500
Data rate	2 kbps (command)	1 Mbps (telemetry) Max: 105 Mbps (Data)

Space Segment: The sampling rate of the sensors is approximately 6 Mbps using a lossless compression factor of 2. Considering the duration of an orbit of 100 min and the case only one of the GS was available, the amount of data to be stored is 37.8 Gbit. An onboard mass memory of 64 Gbit is selected for this purpose. This figure together with the average access time per day (2.64 h) results in a minimum downlink data rate of 79.9 Mbps. As a consequence, the payload data are transmitted in X-band at a data rate of 85 Mbps with QPSK modulation. The downlink budget is driven by the downlink data rate which, at the same time, determines the uplink budget (see table 8). The X-Band antenna is an isoflux antenna as used in ENVISAT which provides a gain of 3.4 dB.

Telecommand & Telemetry: The TT&C unit consists of 2 S-band transceivers using BPSK modulation, each operated in hot redundancy. The antennas provide an omnidirectional antenna pattern to ensure the availability of the TT&C links. TT&C communications conforms to ECSS standards. Transponders do not need the ranging function because the GPS receiver provides the position and velocity of the spacecraft in the earth reference frame.



Table 5: Link budget

Uplink		Downlink	
$P_{sat}$	1 W	$EIRP_{GS}$	104.7 dBm
$G_{sat}$ (X-Band)	3.4 dB	$G_{sat}$ (S-Band)	0 dB
$G_{GS}/T$	41 dB/K	$R_b$	2 kbps
$R_b$	85 Mbps		
Margin	8.6 dB		66.6 dB

### Avionics/On Board Data Handling

The Avionics/OBDH contains all the systems and interfaces which are necessary to operate and maintain the satellite and support the payload. These include systems that support attitude measurement and control, telemetry and command, data storage and retrieval, power generation and storage, and thermal control. It is displayed in Figure 5, including the OBC and the S-Band and X-Band transceivers. The Attitude Determination and Control Subsystem (ADCS) requirements are driven by worst case disturbance torques, which in our case is the magnetic torque ( $4.3044e-5$  Nm).

The attitude control subsystem consists of: four Reaction Wheels (RW) and 3 axis Magnetic Torquers (MGT) for RW and desaturation and control in safe mode. The attitude determination elements are: a Star Tracker (ST), a 3-axis Magnetometer (MGM), 3 Sun Sensors (SS) and a GPS receiver (see Figure 5).

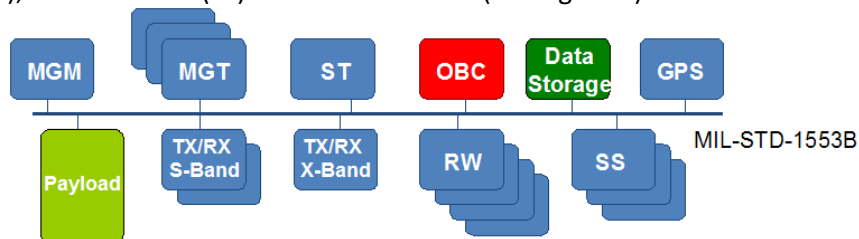


Figure 5 Avionics/OBDH architecture

### Mass Budget for one satellite

Table 6 Mass budget

Subsystem	Mass (kg)	Mass (%)
Payload	74.8	26
Power	71.9	25
Structure	48.9	17
ADCS	23.0	8
Comm	5.8	2
OBDH	8.6	3
Thermal	5.8	2
Propulsion	55.9	17
Total	287.7	100%
20% Margin	58.9	
Total + margin	353.6	



## Power Budget of one satellite

Table 7: Power budget

Component	Avg power (W)	Duty cycle	Typ power (W)
<b>Payload</b>	148.0	100%	148.0
<b>S-band transceiver+antenna</b>	13.0	15%	2.0
<b>X-band transceiver+antenna</b>	31.0	15%	4.7
<b>On board computer</b>	10.0	100%	10.0
<b>Reaction wheels</b>	10.0	100%	10.0
<b>Magnetic torquers</b>	3.1	100%	3.1
<b>GPS receiver</b>	20.0	100%	20.0
<b>Star tracker</b>	8.0	100%	8.0
<b>Sun sensors</b>	2.0	100%	2.0
<b>3-axis magnetometer</b>	0.6	100%	0.6
<b>Power subsystem</b>	41.7	100%	41.7
<b>TOTAL</b>			250.0
<b>Margin(10%)</b>			25.0
<b>TOTAL with margin</b>			<b>275.0</b>

## Cost Analysis

Table 8 contains the cost of the Vesta mission. We use a parametric (mass-based) cost model. The Cost Estimated Relationships (CER) are based on<sup>11</sup>. The budget includes the cost for Research and Development, Theoretical First Unit (TFU), learning curve, and the cost in Fiscal Year 2010 M€ (Costs provided by CER in WERTZ are in FY00M\$ => corrected for inflation and currency change).

Table 8: Cost budget (M€)

Component	Option 1	Option 2	Option 3
<b>Payload (1st unit)</b>	33	33	33
<b>Bus (1st unit)</b>	52	52	52
<b>1<sup>st</sup> satellite</b>	85	85	85
<b>2<sup>nd</sup> satellite</b>	47	47	47
<b>3<sup>rd</sup> satellite</b>	44	44	44
<b>4<sup>th</sup> satellite</b>	42	42	42
<b>5<sup>th</sup>, 6<sup>th</sup> satellite</b>		42	42
<b>7<sup>th</sup>, 8<sup>th</sup>, 9<sup>th</sup> satellite</b>			42
<b>Launches (2)</b>	70	70	105
<b>Operations (7 years)</b>	70	70	70
<b>SUBTOTAL</b>	443	527	687
<b>Margin (20%)</b>	89	105	137
<b>TOTAL</b>	<b>532</b>	<b>632</b>	<b>825</b>

## Launcher

Considering the previous decisions regarding the orbit architecture, the launcher selected for the mission is Vega because it satisfies all the requirements: performance at 800 km and 25° inclination is 1900 kg. Two launches are required with 3 satellites each. The price per launch is 35M€. Since the mass budget concluded that the mass of each satellite is 353.6 kg (total weight: 1035 kg +100 kg of central beam), the limitation is driven by volume not by mass. The solution for the configuration is illustrated in Figure 6.

Kourou is the selected launch site since it satisfies requirements for latitude and azimuth. A considered back up launcher is the PSLV with launch site in India, which has similar dimensions (larger diameter for the payload volume) and lower price (17M\$ per launch).

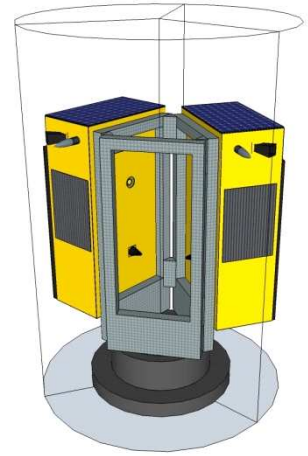


Figure 6: Two of three satellites in launcher configuration

## Propulsion for Subsystem

The propulsion subsystem comprises of a hydrazine monopropellant (EADS CHT-20) with 20N nominal thrust, a 39kg fuel bladder tank (EADS BT 01/0, 39kg fuel capacity) and the He pressurization system with check and pyro-valve. The total mass of the propulsion subsystem including 20% margin is calculated to be m=30.0kg or 55.9kg for Option 1 and 3, or Option 2 respectively.

## 5. Mission Constraints

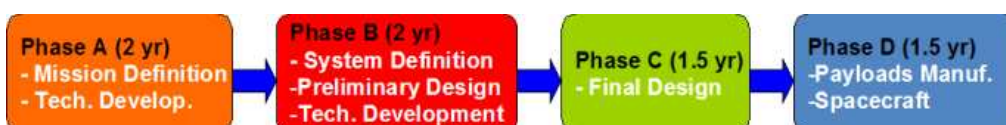
### 5.1 Technological assessment

Table 9: Subsystem/critical components which were considered for Technological Readiness Level are given below.

Subsystem /critical component	TRL	Comment
ADCS	5	Existing, costumisation needed
Data handling & Onbord computer	6	Existing
Instruments		
WAOSS-B Heritage	5	Existing instrument with modification
MIR/TIR Sensor	3	Existing components, rearranging in new design
Propulsion	6	Readily available, space heritage
Power		
Batteries	6	Readily available, space heritage
Solar arrays	5	Technology available, only shape costumization needed

### 5.2 Mission assessment

The mission timeline is given below.





### 5.3 Risk Assessment

Simulation of constellation degradation showed a robust behavior of the constellation regarding the impact of loss of one satellite on average revisit time for Option 2 and 3, leading to an increase of 11.5min and 16.8min respectively. As expected, impact is at most significant for Option 1, where revisit time average would be increased by 45min. The impact of loss of one launch vehicle in the worst case is found to increase average revisit time by 108min, 73.2min and 17.4min for Option 1, 2 and 3 respectively. The impact of launch vehicle failure might be reduced by onboard propulsion capabilities of remaining satellites, depending on the circumstances.

### 5.4 Descoping options

The impact of descoping options on temporal coverage has been presented in Table 3 and the discussion within section 4.2.

### 5.5 Cost assessment

For cost values please see Cost Analysis in 4.3

### 5.6 GMES

The results obtained will be integrated in the Global Monitoring for Environment and Security (GMES) programme to freely distribute them among the interested public.

**5.7 Assimilation** We derived a carbon flux budget which will be an important factor for the climate model.

**5.8 Validation** We plan to validate the sensors of the Vesta satellite with the vicarious cross-correlation between the satellites of the constellation, vicarious validation with polar satellites and with in-situ measurements from a tower.

## 6. Conclusions

Vesta could measure FRP with sufficient spatial, radiometric and temporal resolution to reduce uncertainty of CO<sub>2</sub> emissions. This mission could monitor FRP to provide data for aerosol release and calibration of geostationary sensory. A constellation of four satellites could still give more accuracy data than current missions but would provide reduced temporal coverage.

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