PRELIMINARY DESIGN OF A SMALL SATELLITE CONSTELLATION FOR MONITORING BUSHFIRES IN AUSTRALIA

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ABSTRACT:

Australia is one of the most fire prone countries in the world, as seen from the devastating 2009 bushfires in Victoria. An efficient fire monitoring system could lead to enormous savings in human lives, fauna and infrastructure. One way to address this issue is to launch a space-borne bushfire monitoring system. This paper presents the AusFireSat smallsat constellation initiative. Its payload is based on a camera system for imaging radiation by an optical system onto a linear array sensor. The payload combines middle infrared and thermal data, subsequently downlinked to a ground station at a rate of 7.5 Mbps. The two AusFireSat satellites would be placed on a frozen, circular, 55° orbit, at 700 km altitude, with 180-degree separation. This orbit configuration passively controls the eccentricity and argument of perigee and minimises global and local altitude variations. Also analysed in this paper is the possibility of improving the revisit time by combining efforts with existing sensors, such as the Chinese HJ-1 series satellites. The total dry mass of AusFireSat is predicted to be in the region of 40.52 kg. Based on the characteristics of the payload, a power budget of 32 W is to be incorporated into the power budget design. A 2.7 m^2 Silicon (Si) and Gallium Arsenide (GaAs) solar array will provide adequate power to the spacecraft. Falcon I was selected as the best launch vehicle candidate. The estimated cost of the mission is USD$163M for a 5-year life cycle.

1. INTRODUCTION

Bushfires are a recurrent feature of Australia's environment and cause significant impact on biodiversity and threaten human lives, property and livestock. The carbon cycle is also affected, due to the emission of atmospheric greenhouse trace gases (Russell-Smith, 2007). As an example of the magnitude of this problem in Australia, hundreds of thousands of hectares were burnt in Victoria in 2009. The loss of human life and property has prompted governments to find strategies to provide authorities with early warning**.** An efficient fire monitoring system could therefore lead to enormous savings in human lives, fauna and infrastructure. Space-borne monitoring missions have in the past proven the effectiveness and feasibility of an early-warning system. The National Oceanic and Atmospheric Administration (NOAA) launched the relatively coarse-resolution Advanced Very High Resolution Radiometer (AVHRR). Daily observations were made with a pixel size of approximately 1.1×1.1 km^2 at orbital nadir. More recent missions such as the *Terra* and *Aqua* constellations launched by the National Astronautics and Space Administration (NASA) acquired data with a resolution of 250m in the along and cross-track directions. The China Earth Observation Satellite Program launched the HJ-1A and HJ-1B constellation, which acquire data with a resolution of 150 and 300 m in the mid-infrared and thermal spectral ranges respectively.

This paper investigates the design of an experimental fire detection payload together with orbital parameters of a satellite platform. The payload would be of enormous benefit to Australia as well as many other fire-prone countries. The paper is a preliminary estimate of mission needs, requirements and constraints. The first section of this paper elaborates on the mission requirements and required satellite performance. Then section IV describes the areas of coverage and the process of orbit selection. Different constellation configurations are also analysed in this section. Section V describes the transmission of collected payload data. Finally, section VIII provides a preliminary cost analysis of the mission.

2. MISSION OBJECTIVES

The primary objective of the AusFireSat mission is to detect, identify and monitor in real time bushfires throughout Australia,. The satellite will also provide global data, but this event is incidental to the main mission requirements. Further mission objectives will include demonstrating to the public that positive actions are underway to contain forest fires; to demonstrate Australia's technical expertise and excellence in remote sensing; to collect statistical data on the outbreak and growth of forest fires; to monitor forest fires for other nations; and last but not the least, to collect other forest management data. As an extension to this, it would be beneficial to identify areas of high bushfire risk to provide early warning for action and to determine any patterns arising, such as reoccurring fires in the same locations. The principles guiding the design of the payload are: rapid response; high reliability; adequate location accuracy; and ability to determine the spread of a fire.

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3. PAYLOAD PERFORMANCE

The two most distinguishing features of a natural fire, particularly a luminous one, are its apparent source temperature and the power spectral density of the radiation intensities emitted from the fire (Yudaya, 2001). This increased radiation emission is particularly obvious in the mid-infrared region, as governed by the Plank function (Li, 2001). Therefore, the most effective method for detecting active fires is to measure the thermal emission at the scene.

Considering the mass constraints of a small satellite mission, the use of an imaging sensor in the visible optical domain was excluded from the design. Although smoke is more evident in the optical spectral range, distinguishing between smoke and cloud cover is challenging with optical sensors. The payload consists of a two-band sensor: Band 1, with 4.2 μm wavelength operates in the mid-infrared region; Band 2 with 10 μm wavelength operates in the thermal infrared region. Infrared sensors measure the emissivity of the scene, which can operate both day and night. This is of special importance since the mission requirements call for constant bushfire monitoring.

Each sensor band will look at specific attributes of a fire. The mid-infrared band is the most useful in bushfire detection (Li, 2000). This hypersensitivity to the presence of fire can cause significant channel saturation. To overcome this issue, both mid-infrared and thermal channels should be used concurrently. Band 1 was specifically selected to avoid water vapour absorption and to reduce the effects of reflected solar radiation.

For AusFireSat the method to be employed for bushfire detection is an extension of the algorithm developed using AVHRR. Initially, the algorithm estimates the background temperature for pixels containing fire. It then searches for pixels with digital numbers below a certain threshold. Low digital numbers correspond to high radiant power. Problematic pixels are then grouped together to form a *hot spot*. These areas are highly indicative of fire prevalence (Wertz, 2003). In addition to the spectral analysis of each individual pixel, the algorithm calculates the deviation angle between the direction of the reflected sunlight and the line of sight from the target to the sensor. A *hot spot* is only considered a fire if certain criteria are fully met. The most important criterion states that for a fire to be present, the deviation angle must be greater than a pre-determined threshold (Rauste, 1996). The next step in the algorithm eliminates false readings due to sun glint and consolidates fire readings from adjacent pixels to eliminate redundant reports. Furthermore, the sensor estimates the total emitted energy in the mid-infrared channel. Finally, the status of the fire is classified as either smoldering or flaming.

According to the mission requirements, the minimum ground pixel resolution required for bushfire mapping is in the range of 100-200 m, measured in the along and cross-track directions.

4. PAYLOAD PERFORMANCE

The primary mission objective is to monitor bushfires in the Australian continent. Australia is located between the latitudes of 10 degrees south and 46 degrees south. Bushfires also affect large areas of Southeast Asia, southern Europe, equatorial and southern Africa and South America. As per the mission requirements, coverage of other fire-prone regions should be considered in the initial design (Figure 1).

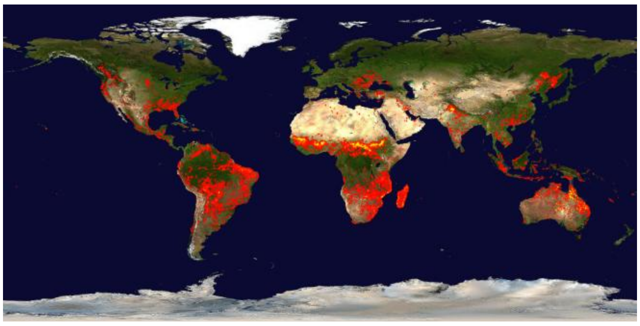

Figure 1. Locations of fires accumulated by MODIS over a period of 10 days. Picture courtesy of NASA**.**

The orbit of a spacecraft is largely dependent on the mission objectives and payloads. In the case of AusFireSat the orbit is determined by the following mission and payload requirements:

- Global coverage (above 65° south and below 65° north) is needed to monitor bushfire prone areas.
- Eccentricity and argument of perigee should be kept constant, to minimise the amount of propellant needed for station keeping. Near-circular orbits require minimal orbital station-keeping;
- A smaller distance between the sensors and studied areas will offer a better resolution.
- To maintain the launch costs to a minimum, the mass of the spacecraft bus and payload should be less than 100 kg.

Taking in account these requirements, a 55° inclination orbit was selected. This configuration ensures coverage within the required latitude boundaries. The perturbing force caused by the Earth's oblateness has an impact on the orbital plane and the eccentricity vector. To counteract this effect, a frozen orbit was selected for this mission. The main characteristic of this type of orbit is that the period of the orbit perturbations is the same as the orbital period. By mitigating the effect of the oblateness vector, this configuration passively controls the eccentricity and argument of perigee and minimises global and local altitude variations. This enables repeated observations of the target scene under constant observation conditions.

To select a suitable orbit altitude several aspects were considered, namely the required velocity differential ΔV to launch the payload; cost constraints; orbit maintenance due to atmospheric drag; coverage; required resolution on the ground and satellite budgets. To achieve the required resolution and coverage, a low earth orbit (LEO) configuration was considered. with altitudes between approximately 500 and 1500 km, which meet the requirement of a small distance between the satellite sensors and the target scene. Counteracting the effect of atmospheric drag was an important design consideration. Selecting an orbital altitude that is too low would incur a significant mass penalty, due to increased amount of propellant required for orbital station keeping. Conversely, selecting an orbital altitude in excess of 800 km would have had an adverse impact on parameters such as resolution, launch costs and orbit maintenance (Wertz, 2003). Concluding, AusFireSat will be placed onto a 700 km frozen-orbit, at an inclination of 55°.

Table 1 shows the Figures of Merit for the orbit described above:

Table 1: Orbital Elements for AusFireSat

Parameter	Symbol	Value
Semimajor axis (km)	A	700
Eccentricity	E	0
Inclination (deg)	I	55
Period (min)	P	98.77
Ground Velocity (km/s)	V_g	6.76
Node Shift (deg)	ΔL	24.76
Right Ascension of the Ascending node (deg)	Ω	100.419

Using the selected orbit parameters, the sensor viewing parameters can be defined. Parameters such as angular radius of the Earth (ρ) and maximum distance to the horizon (D_{max}) are directly derived from the orbital altitude. Other parameters such as the earth's central angle (ECA), the elevation angle and the maximum incidence angle were constrained by the required resolution and coverage. To calculate the remaining angles, some assumptions must be made, based on the mapping requirements. To achieve high resolution and mapping accuracy, the satellite field-of-view must be adjusted accordingly. Resolution and mapping accuracy must be traded with coverage (Wertz, 2003). Considering this trade, to achieve a FOV of 20° and a ground pixel resolution of 100x100 m, a spacecraft elevation angle (ε) of 78.9° was chosen, yielding an Incidence Angle (IA) of 11.2°, and swath width of 2.3°. Using the viewing parameters and known instrument specifications (focal length, f = 0.21 m, number of bits used to encode each pixel, B = 12), the pixel parameters data rates can be defined (see Table).

Table 2: Pixel Parameters and Data Rate

Parameter		Value
Max. Along track sampling distance	Ymax (m)	102.00
Instantaneous Field of View	IFOV (deg)	0.0082
Max. Cross-track pixel resolution	Xmax (m)	103.95
Cross-track ground pixel resolution	X (m)	100.28
Along-track ground pixel resolution	Y (m)	100.28
No. of cross-track pixels	Zc	2435
No. of swaths recorded along track	Za	67.4
No. of pixels recorded in 1 sec.	Z	164197.68
no. of bits used to encode each pixel	B (bits)	12
Data Rate	DR (Mbps)	1.97

4.1 Revisit time for single satellite

Considering the orbit and optics of the sensor, the coverage provided must be assessed. Assuming that the mapping process will take part during daylight and shadow hours, the local time of the descending node of the orbit occurs at 12:00:00.000. The complete ground revisit-time of the affected areas can achieved in approximately 15 days. This figure could be improved by increasing the field-of-view. The effect of this, however, would be at the cost of the sensor's ground resolution.

For a single satellite during a trial period of 14 days, the Australian continent will be under observation approximately 4% of the total observation time. The improvement of this figure will be addressed in the next section.

4.2 Constellation design

Given the low field-of-view and the mission requirement of round-the-clock monitoring of bushfires, the issue of low coverage must be addressed. One way to address this is to employ multiple satellites in a constellation configuration. This could either involve designing an entirely new constellation, or rather adding a new satellite to an existing constellation, such as China's HJ-1 series. Integration of the AusFireSat payload with an existing constellation could theoretically reduce the costs of deployment. In practice, however, this may be unlikely due to the political nature and sensitivity of data collected by some of the existing constellations Furthermore, adding a new satellite is a systems integration challenge. The increased data download requirements would add to the overall mission costs. On-going maintenance costs would also increase considerably (Russell-Smith, 2007). At this stage, existing constellations are therefore ruled out. An entirely new constellation configuration must be designed. The best coverage can be achieved by deploying several satellites with different inclinations. Several configurations were considered, including: 2-plane polar, mutually perpendicular planes and perpendicular non-polar planes. This practice, however, is extremely difficult to achieve because satellites will regress at different rates, as the rate of nodal regression is a function of altitude and inclination. A constellation with multiple orbit planes is also less responsive to changing user needs. Furthermore, maintaining constant constellation spacing would require large amounts of propellant, thereby increasing the amount of propellant required. Therefore, the AusFireSat constellation will consist of two satellites orbiting in the same direction, in a single orbit plane. The spacing between satellites determines whether the coverage in the orbital plane is continuous. It also determines the width of the continuous coverage region. This will ensure maximum continuous coverage on the ground. The satellites will have an 180º spacing.

4.2.1 Revisit time for two-satellite constellation

A key aspect in the design of a constellation is to maximise the area of overlap between both satellites' ground tracks. By increasing the amount of overlap, the revisit time can be significantly increased. The amount of overlap is a function of the sensor's field-of-view. A 7-day revisit time can be achieved with a two-satellite constellation in the configuration described above. In practice, however, revisit time can be increased to approximately 4 days if ground tracks overlap. For a 14-day trial period, the Australian continent was under observation for approximately 8.5% of the total observation time. This constitutes an improvement of 4.5% over a single satellite configuration.

4.3 Detector Configuration

A push broom configuration was selected for the on-board sensor. The sensor works by scanning a linear array of across-track pixels per integration time as it moves along-track. Push broom sensors are typically used for remote-sensing missions, as they provide a low mass, low-cost solution. Furthermore, these types of sensors absorb more photons, due to the increased integration time, when compared with it whisk broom sensors. The main disadvantage of push broom sensors, however, is the rather complex optics required (Wertz, 2003).

The selection process of the detector elements depends on criteria such as the number of elements required and the spectral range of the instrument. The latter determines the type of material used. To achieve the required across and along-track resolutions of 100 metres, 2476 silicon detectors must be incorporated into the line imager. This also ensures that the 20° field-of-view requirement is fulfilled.

5. RESPONSIVENESS

Communications is an integral part of any space mission. It is important that the satellite can receive and transmit information, from telemetry data to scientific data, acquired by the payload.
It is proposed that Mission control for AusFireSat will be located at the ACRES-operated Alice Springs ground facility. This ground station will be used to upload re-positioning commands if required and to receive payload data packages. Transmission of data does not rely on illumination conditions, and so can occur in ascending and descending durations of the orbit. Using simple conical communication sensors, the access time between the satellite and the ACRES ground station is on average 33 minutes in a 24-hour period. In order to determine whether this would be an adequate time allowance, three factors must be considered: the time-sensitiveness of the information gathered; the time required to download data collected during the out-of-access time; the data storage capabilities of the payload.

As per mission requirements, the information gathered on bushfires is extremely time-sensitive. Daily updates are therefore required. The size of the download file can be estimated using the data rate of the sensor (1.97 Mbps - see Table 2). Considering the sensor captures data continuously over a 24-hour period, 171040.4 Mb of data are collected daily.
Several other potential ground stations are listed in Table 4. Ground facilities were selected based on the antenna diameter requirement of 11 metres.

Table 3: Global Ground Stations

Facility	Latitude	Longitude
Quito (South America)	-0.217°	-78.5°
Liberville (Africa)	0.355°	9.657°
Carnicobar (Asia)	9.149°	92.815°

With the additional ground stations, access time to the satellite increased to approximately 2.5 hours. The spacecraft antenna diameters were consequently reduced to 0.5 m. A typical on-board recorder with the capacity of up to 134Mb was therefore chosen**.**

6. SIZING THE SPACECRAFT

Having determined the mission payload, it was then possible to start to further develop the design of the spacecraft. Mass Budgets can be determined (Table 4) using the method described by Brown *et al* (2002). The payload constitutes 31% of the total spacecraft mass. The remaining mass is subsequently allocated to the other subsystems. The total dry mass of AusFireSat is predicted to be in the region of 40.52 kg. The wet mass (fuelled) was predicted to be 50.65 kg using contingencies of 50% and propellant allowances suggested by Wertz (2003). A Power Budget to be incorporated into the AusFireSat design was determined using the method described by Wertz *et al* (2003) (Table 5). A total of 31.71 W is needed to power the spacecraft subsystems and payload.

Table 4: Mass Budget

		Mass (kg)
Payload	IR sensor	3.7
	Electronics	4
	Solid state recorders	1.64
Payload total		**9.34**
Subsystem	**% Mass**	**Mass (kg)**
Structure	20	6.03
Thermal	8	2.41
ACS	9	2.71
Power	16	4.82
Cabling	3	0.90
Propulsion	5	1.51
Telecom	4	1.21
CDS	4	1.21
Payload	31	9.34
Mass subtotal	**100**	**30.13**
On orbit dry[a]		40.52
Wet[b]		**50.65**

[a]50% subsystems mass margin
[b]25% propellant mass margin

An estimate of power sources can be determined using the total power required for the spacecraft. Solar Arrays based on Silicon (Si) cells with an area of 2.7 m^2 are the primary power source whilst the spacecraft is illuminated. Silicon cells were chosen for their low mass.

Table 5: Power Budget

		Power (W)
Payload	Camera Head	1.43
	Electronics	5.49
	Solid state Recorders	6.8
Payload total[a]		**15.86**
Subsystem	**% Power**	**Power (W)**
Thermal Control	48	7.61
Attitude Control	19	3.01
Power	5	0.79
CDS	13	2.06
Communications	15	2.38
Power subtotal	**100**	**15.85**
Spacecraft total[b]		**31.71**

[a]10% contingency
[b]50% payload power allocation

The solar arrays will provide adequate power to the spacecraft whilst it is illuminated by the Sun. However, once it enters into the Earth's shadow, alternative forms of power need to be considered, such as batteries. The solar array calculations have already incorporated this extra power storage requirement. Two battery options available to the AusFireSat mission are Nickel Cadmium (NiCD) and Nickel Hydrogen (NiH). Based on their respective capacities, density and depth of discharge (DOD), and masses, NiH batteries were selected due to their lower mass of 0.775 kg.

7. LAUNCH VEHICLE

The launch vehicle selection process is closely related to the performance of the launch system, trajectory and mass requirements. In order to select the appropriate launch vehicle, a clear understanding of the mission needs is required. The first factor to be considered is the payload mass. This factor directly influences the type of launch strategy. Shared launches are often used as a way to reduce launch costs, by delivering several payloads simultaneously. The downside of this configuration, however, is the increase in the complexity of the vehicle mechanisms and structure. A dedicated launch, on the other hand, offers increased reliability, but with higher associated costs. Selection of a launch vehicle is also dependent on other factors such as vehicle availability, budgetary constraints and cost-effectiveness. Several candidates were analysed, namely Taurus, China's CZ1D and Falcon 1. Falcon 1 meets AusFireSat mission criteria due to its low cost coupled with the fact that it can launch a payload of up to 600 kg.

8. COST ESTIMATION

The analysis and prediction of program cost is critical to determining whether a mission is viable. The main challenge of this analysis is to maximise performance whilst maintaining costs within the budget. The payload is the main driver of the mission: according to estimates by Wertz *et al* (2003), 40% of the cost of the spacecraft should be allocated to the payload. The cost of a smallsat mission is a parameter that varies depending on factors such as: size of the spacecraft, design life and scheduling, risk tolerance, and government budgets. To make an accurate estimation of the mission costs, a work breakdown structure (WBS) approach should be followed. This methodology, however, relies on the individual costs of each mission subcomponent. Given the very uncertain nature of the early planning stages, the method followed in this work is based on parametric cost estimation. A series of mathematical relationships relate cost to physical, technical and performance parameters that are known to strongly influence costs. These parametric estimations incorporate equations known as *Cost Estimation Relationships* (CER). Parametric cost modelling is based on available historical data for missions of similar specifications. CERs are therefore a function of the statistical quality of available regression analysis. The total space and launch segment costs can be broken down into three phases: the *Research, Development, Test and Evaluation* (RDT&E), *Production* and *Operations and Maintenance* (O&M). The first phase defines the mission architecture. It includes the design, analysis and test of prototypes. The second phase includes the production of the *Theoretical First Unit* (TFU), which in the case of a two-constellation mission represents the production of the first satellite. A learning curve is applied to the TFU to calculate the costs of subsequent units. The costs of launch are also included in this phase. The *O&M* phase incorporates the cost of on-going operations and maintenance. Table 1 in the Appendix shows an estimated cost of USD$77M for both RDT&E and TFU phases. Table 2 in the Appendix section shows an estimated cost of USD$6M per year for on-going costs and maintenance. The total life-cycle cost is estimated at USD$163M for a 5 year mission.

9. CONCLUSION

The paper outlines the preliminary design of AusFireSat, a small satellite constellation designed to detect, identify and monitor bushfires throughout Australia and globally, in real time. The payload combines mid-infrared and thermal data. The two AusFireSat satellites are on a frozen, circular, 55° orbit, at 700 km altitude, with 180° separation. The total mass AusFireSat is predicted to be approximately 51 kg. Based on an infrared sensor payload, a power budget of 30 W is to be incorporated into the budget design. A 2.7 m^2 Silicon (Si) solar array will provide adequate power to the spacecraft whilst it is illuminated by the sun. The estimated cost of the mission is USD$163M for a 5-year life cycle. This paper shows that at this stage the bushfire tracking mission is feasible with smallsats. It would therefore be advantageous to proceed with the mission plan, incorporating a much more detailed analysis of additional payload requirements and configurations.

10. AKNOWLEDGEMENTS

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12. APPENDIX

Table 7: AusFireSat Space and Launch Costs

Cost Component	RDT&E Cost (FY11$K)	1st Unit Cost (FY11$K)	2nd Unit Cost (FY11$K)	Total Cost (FY11$K)
1. Payload	2,961	1,985	1,786	6,732
2. Spacecraft bus				
2.1. Structure	858	368	331	1,557
2.2. Thermal	339	339	305	982
2.3. EPS	3,238	1,985	1,786	7,009
2.4. TT&C	614	251	225	1,090
2.5. ADCS	1,811	3,083	2,774	7,669
2.6. Propulsion	543	543	489	1,576
Spacecraft bus total cost	**7,403**	**5,074**	**4,566**	**17,043**
3. Integration, assembly and test	n/a	900	810	1,710
4. Program level	2,123	2,123	1,908	6,153
5. Ground support equipment	612	n/a	n/a	612
6. Launch and orbital ops support	n/a	565	n/a	
7. Flight software	7,081	n/a	n/a	7,081
Total space segment cost to contractor	17,218	10,399	9,358	36,975
10% contractor fee	1,722	1,040	935	3,696
Total space segment cost to government	18,940	11,438	10,294	40,672
8. Launch segment	n/a	13,000	13,000	26,000
Total cost of deployment				**66,672**

Table 8: AusFireSat Annual Operations and Maintenance

Operations and Management	Cost (FY11$M)
10 Contractor Personnel ($160K/yr)	1.6
Maintenance	4.4
Total annual cost	**6**

Table 9: AusFireSat cost of deployment

Development	Cost (FY11$M)
Software 100 LOC (Ada) @ $220/LOC	27.5
Equipment	22.3
Facilities	5
Subtotal	**54.8**
Management	5
Systems Engineering	8.3
Product Assurance	4.1
Integration and Test	6.6
Logistics	4.1
Total	**83**

Table 10: AusFireSat Life-Cycle Cost Estimate

Initial deployment	Cost (FY11$M)
Space segment	40.7
Launch segment	32.5
Ground segment	83
Subtotal	156.2
Annual Ops and Maintenance	7.5
Total Ops and Maintenance for 5 years	37.6
Total life-cycle cost for 5 years	**193.8**