Evolution and Radiative Impact Contrails-Cirrus: the ERICC Mission

Abstract. This report summaries a newly-proposed space mission for the understanding of climate change - ERICC (Evolution and Radiative Impact of Contrail Cirrus). ERICC aims to better constrain the amount, evolution and radiative impact of anthropogenic contrail cirrus in Earth's atmosphere. The formation of thin cirrus is influenced by contrails formed in the upper troposphere by jet airliner exhaust emissions. With global air traffic projected to increase dramatically in coming years, it is critical to constrain the extent of contrails' influence on climate change. ERICC is a constellation of eight satellites, each carrying identical multispectral imagers specifically designed to identify and track contrails, and their subsequent development into cirrus.

1. Science background

Cirrus clouds are ice clouds found in the upper troposphere, and are believed to cover approximately a quarter of the globe at any time. Cirrus clouds affect the Earth's radiation balance by reducing the amount of short–wave radiation reaching the surface, and reducing the long–wave radiation emitted back to space. Theoretical calculations suggest the long-wave impact is greater, but the overall impact is strongly dependent on the physical properties of the specific cloud. A major uncertainty associated with the climatic impact of cirrus is the role played by contrails (condensation trails) which are optically thin linear upper tropospheric trails formed by the interaction of jet airliner exhaust emissions with the ambient atmosphere. Contrail cirrus is predicted to form in locations where the atmosphere is supersaturated with respect to ice. Here, aerosols in the jet exhaust - H_2SO_4 and soot - act as nucleiation surfaces where ice crystals can form.

As with natural cirrus, the radiative impact of contrail cirrus is not well understood. Studies have suggested that due to the higher concentration of small ice particles in contrail cirrus, the short-wave impact may dominate over the long-wave effect. As before though, there is no current sense of their global impact.

However, it is known that global air traffic is increasing, and is forecasted to increase further in coming years (Figure 1). Hence, it is crucial to develop a quantitative understanding of the role of contrail cirrus have on the Earth's radiation budget as it is likely to become increasingly significant.

Yang et al. (2005) mentions an urgent need to improve the satellite detection of contrails and their development into contrail cirrus, and recommendsaccurate determination of contrail and contrail cirrus in terms of their coverage, optical properties, and radiative forcing from a variety of satellite data sets. This knowledge is important in order to understand the role contrails have in Earth's climate.

1.1. Mission overview

Our mission aims to better observe the development of contrails into persistent contrail cirrus, and their impact on the Earth's radiative balance. This will be done using a constellation of eight satellites that will achieve a combination of better temporal and spatial resolution than that currently available. ERICC will observe the amount of contrails formed in major air-traffic corridors and track the evolution of contrails into contrail cirrus.

The instrument for achieving the observational requirements will be a multispectral imager using pushbroom technology. The onboard radiometers will allow the measurement of 7 different wavelength bands spanning the visible to thermal infrared spectral domain.

Figure 1. Projected increase (in tonnes) and annual growth rate of total world freight traffic between 2005 and 2025.

The ERICC constellation satellites will be placed in orbits at a height of 567 km and an inclination of 60^o with an angular spacing of the ascending node of 15^o. In this way, particular locations will be sampled every hour for eight consecutive hours. The compact spacecraft design provides accurate pointing mechanisms for observation and fast data download, as well as appropriate thermal and power margins, allowing operation also during eclipses. The design is based on robust space-qualified components, most of them with space heritage, which ensures high reliability. The selected ground segment provides contact with each satellite for 11 orbits per day.

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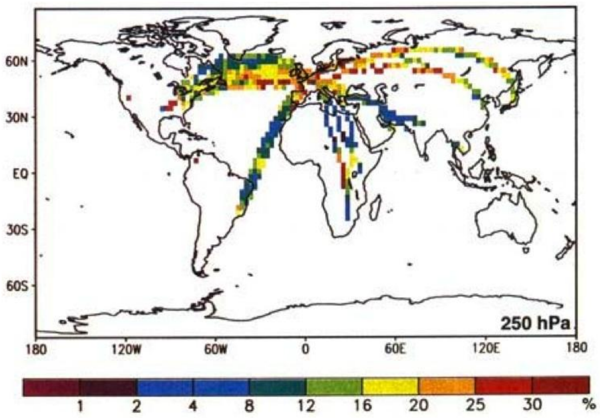

Figure 2. Probablity (%) of ice supersaturation ($Rh_i \geq 100\%$) in a 50 hPa thick layer centered at 250 hPa, based on humidity and temperature measurements from the MOZAIC project, 1995–1997.

Contrail and contrail cirrus formation occurs in ice-supersaturated regions. This typically occurs at temperatures below -39^oC (234K) and at pressures lower than 300hPa, which is in the region of the upper troposphere [Minnis, 2004], [Schumann, 2005]. The degree of ice supersaturation, based on data measured from aircraft, is shown in Figure **??** b). Particularly high probabilities ($> 20\%$) are found over parts of the Northern Atlantic, over mainland Europe and Asia (between 50^oN and 60^oN) [Gerens, 2000].

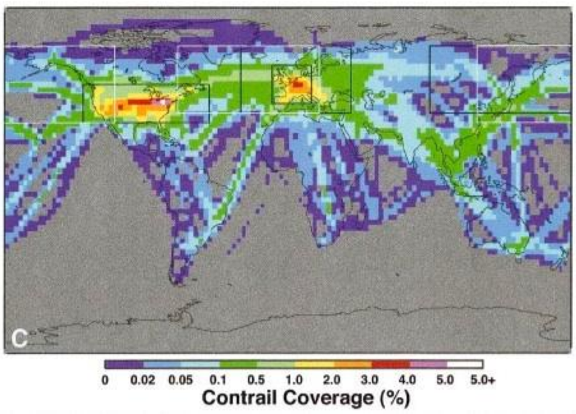

Figure 3. Estimated global contrail coverage in 1992.

1.2. Science Objectives

1.2.1. To better constrain the amount of contrails generated by air traffic

Major air corridors are concentrated between 60^oN and the equator (Figure 3), with the North Atlantic corridor between Europe and the USA containing the densest traffic. The ten largest air hubs are also located either side of this corridor; it is the most important area of potential contrail cirrus formation.

We will use the Contrail Detection Algorithm (CDA) of Mannstein et al (1999) to locate the contrails formed in our area of interest. The CDA considers thermal infrared brightness temperatures at 10.8 and 12.0 μm and an image processing sequence to distinguish contrails based on their linear continuity. High spatial resolution is key; contrails are only 200 m wide when newly-formed.

The CDA's accuracy has been tested via comparison with general circulation model predictions of contrail coverage. A study over Western Europe found that CDA estimates were underestimated by 50%. This figure is due both to the coarse spatial resolution (1 km) of the satellite instrument used in the study and the fact that the CDA cannot track a contrail which has evolved and lost its linearity.

1.2.2. To observe the evolution of contrails into contrail cirrus

We will use the Automatic Contrail Tracking Algorithm (ACTA) of Vasquez-Navarro et al (2010) to monitor contrail evolution. ACTA's inputs are contrails detected by CDA and upper troposphere wind data from ECMWF, and by identifying the evolving contrail as a group of pixels in space and time. The algorithm is able to track contrail growth and movement.

ACTA has certain key requirements. High spatial resolution is again mandatory. A reasonable swath width enables tracking of the developing contrail cirrus over large distances. A rapid revisit time by the satellite is essential for sampling multiple stages of contrail evolution (linear shape can be lost in ~ 2 hours; total lifetime may only be 7 hours). Spectral bands suitable for identifying contrail cirrus clouds over various surface types are also key.

The mission will also provide insight into the processes governing contrail to cirrus evolution. By combining meteorological data with the mapped contrail distributions we can determine how well theoretical relationships (such as those linking ice supersaturation to contrail formation) are reflected in the real atmosphere.

1.3. Futher Algorithm details - CDA and ACTA

The Contrail Detection Algorithm, CDA [Mannstein, 2000], was originally applied on the Advanced Very High Resolution Radiometer (AVHRR) in several case studies (e.g.). It uses two thermal infrared channels, $10.8\mu m$ and $12.0\mu m$, to distinguish cirrus clouds from water clouds. Input data for the detection algorithm are the equivalent blackbody temperature at $12.0\mu m$ and the brightness temperature difference $10.8\mu m - -12.0\mu m$ (BTD). After applying a highpass filter, normalizing the images and calculating the gradient a mask fulfilling several requirements is retrieved. To be regarded as a contrail the remaining pixel in each object have to fulfill criteria, e.g. more than 10 pixels form the object and the length has to be more than 16 pixel distances.

Linear contrails can be identified in satellite images with the Contrail Detection algorithm (CDA), but older contrail cirrus provide less easily identifiable signals in a satellite image and cannot be distinguished from natural cirrus clouds if their previous histroy is unknown. In this case, an Automatic Contrail Algorithm, ACTA [Vazquez-Navarro, 2010], will be deployed on the result of the CDA.

It exploits the fact, that contrails and contrail cirrus retain parts of their linear structure as they age, and although wind shear and spreading can modify their shape [Mannstein, 2000]. Since the CDA can miss contrails within a field of contrail cirrus, it is important that scenes of ERICC analyzed by the ACTA at the time t are applied to the scene at $t + \Delta t$ to prohibit double detection of contrails and contrail cirrus. Similar to the CDA, ACTA uses the BTD. A rough flowchart of ACTA is given in figure 5.

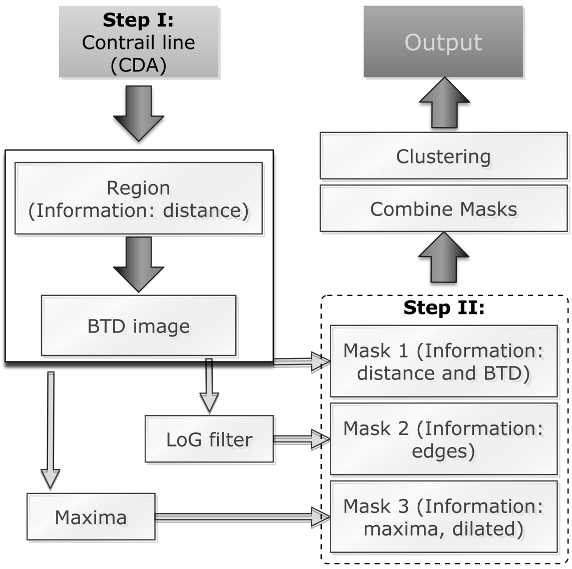

Figure 4. Flowchart of the Automatic Contrail Tracking Algorithm (ACTA).

1.3.1. To better constrain the radiative impact of contrails and contrail cirrus

The radiative impact of contrail cirrus is dependent on certain physical cloud parameters: effective particle radius (R_e), the ice water path (IWP), the optical depth (τ), and the vertical position of the cloud, manifested in its cloud top temperature and cloud top height. We have chosen spectral bands which are sensitive to these parameters. The visible (VIS) and short-wave infrared (SWIR) bands (0.66 μm and 1.66 μm) are highly sensitive to R_e, IWP and thus τ. The 10.8 μm and the 12.0 μm are also sensitive to the same parameters, but need to be combined with additional bands for accurate results: VIS/SWIR bands during daytime and the 3.9 μm mid infrared (MIR) band during night. The TIR bands are sensitive to cloud top temperature and height.

The five bands specified above are the minimum requirements to recover the desired cloud parameters. We have incorporated two additional SWIR bands, 1.38 μm and 1.24 μm due to their use in detecting very thin cirrus.

In order to retrieve cloud parameters from the measurements, we will use lookup tables. These will be generated by radiative transfer modelling, and contain simulations of brightness temperatures and reflectances across the relevant wavelengths as a function of the cloud parameters. By matching the observed data to the lookup table values, users can recover the cloud properties.

1.4. Secondary objectives

The temporal and spatial resolution of the ERICC mission also means that the data can contribute to studies of other important climate parameters.

1.4.1. SST and LST

Two of the bands used by the ERICC mission (3.9 and 10.8) are also used by for example, the MODIS instrument to measure sea surface temperature. Similarly MODIS uses the 10.8 and 12.0 bands for measurements of the land surface temperature (LST). As the ERICC mission includes all of these bands, deriving LST and SST could be a secondary objective. The high spatial and temporal resolution of ERICC provides new data that will complement existing SST and LST databases.

1.4.2. Fire detection

The bands used in the ERICC mission can also be used to detect fires. Among others the MODIS instrument use the 1.66, 3.9, 10.8 and 12.0 for fire detection (Justice et al., 2006). As the ERICC mission will not give real-time data these measurements can not be used for disaster management, but they might prove useful for monitoring the effects of fires.

1.4.3. Combination with other planned missions

The planned SENTINEL 5 and the proposed PREMIER mission of ESA will measure aerosols and water vapor. They will also measure CO_2, NO_2 and SO_2 and have coarser temporal and horizontal spatial resolution than our mission, but some connections between contrail cirrus development and the aerosol and chemical composition might be retrieved with a statistical approach.

2. Mission Constrains

2.0.4. User Data processing

In addition to raw data, the main ground station must be in charge of the algorithms and calibration files (Level 1A and 1B). Then it is available to users who have to provide the physical values about contrails (Level 2 data).

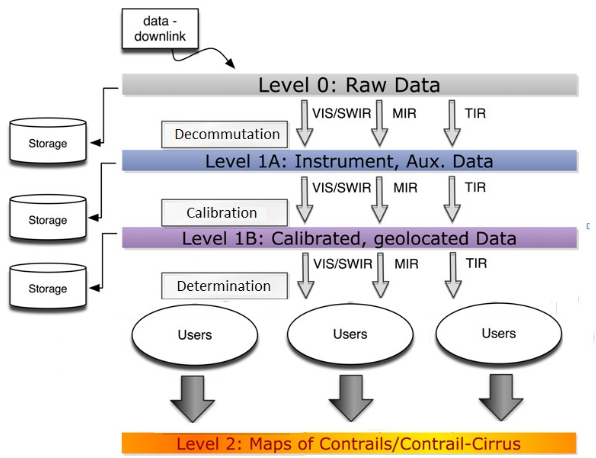

Figure 5. Flowchart of User Data processing.

2.1. Risk Assesment

The three main risks of the mission are

1. Delivery delay of payload, which would delay the whole production schedule.
2. Technology use of TRL 8 or above represents little risk - only the batteries present certain challenges.
3. Avoidance of single time of failure due to satellite redundancy.

2.2. Cost Assesment

The total cost of the mission would be 195 million euros, taking into account labour, spacecraft, payload, ground segment and the launcher.

2.3. Descoping

There are several options to reduce the cost of the mission. First, the number of satellites could be reduced. This would reduce the time resoultion of the mission. There could either be a shorter satellite-per-hour time window (e.g. 09-15), or the time interval between the satellites could be increased. This would significantly affect the scientific objective. The second option is to reduce the number of spectral bands. This will reduce the costs, the power consumption and the mass of the satellite. The scientific impact would be to lose the ability to observe the contrails over some surface types (e.g. over ice/snow).
There is also an option to reduce the amount of pixels in the detectors. This will reduce costs, mass and power contumption, but the swath width or the spatial resolution would have to be reduced. This will largely affect the mission objectives. The fourth option is to replace the HgTeCd detector with micro bolometers. This option will produce lower costs, mass and power consumption (since there is no need for cooling), but at the cost of using less precise and mature tecnology. The reduced precision will somewhat affect the mission objective. Only the reduction of the number of satellites will significantly reduce the costs of the mission. But having only 8 satellites, is already on the limits of achieving the scientific objectives of the mission, and reducing this number further is not recomended.

2.4. Timescale

According to the project schedule, the preparation phase of ERICC could be completed within 48 months due to the use of state-of-the-art technologies.

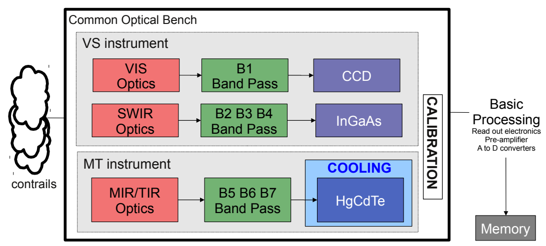

Figure 6. General design of the payload.

3. System Design

3.1. Payload definition

The ERICC payload consists of two multi-spectral sensor instruments. The instruments are designed to provide images of the visible and infra-red at the chosen wavelengths and bandwidths. The instruments use the pushbroom scanner (along-track scanner) technology, in nadir orientation. The 200 m x 200 m resolution requirement is being fulfilled by 1 x 2048 pixel sensors and a nominal dwell period of approximately 26 ms. We shoud note that the detectors are read-out 5 times during the dwell period, to avoid saturation.

Each instrument consists of a single box containing all optical, electronic and mechanical elements. Large radiator areas are available for heat dissipation to provide a stable environment for the VIS/SWIR or the MIR/TIR detectors. The payload will be constructed in four main units:

- the VIS/SWIR instrument, providing data from four spectral channels.
- the MIR/TIR instrument, providing data from three spectral channels.
- a common bench optical module that interfaces with the platform. The bench is located outside the main platform structure, with the control inside.
- the instrument control unit that drives both the VIR/SWIR and the MIR/TIR instruments.

The absolute accuracy of the radiometers is corrected by monthly calibration using different hot and cold targets, depending on the wavelengths.

3.1.1. VIS/SWIR Optical Design Description

The VIR/SWIR system optical design is shown in figure 7. Dichroic splitters can reduce the size of the calibration diffuser by providing a common aperture for all four channels. Since a common entrance pupil (aperture) is necessarily remote from the lenses, we should point out that dichroics tends to enhance the optical system size.

3.1.2. VIS/SWIR Sensors Description : silicon charge coupled detectors (CDDs) and indium gallium arsenide (InGaAs)

As the operating temperature of both the CCD and InGaAs detectors fits within the -10 °C, +40 °C interval, no more thermal control than some copper heat exchangers is necessary. The need for a 1 x 2048 pixel line will require further collaboration with manufacturers as no InGaAs of that

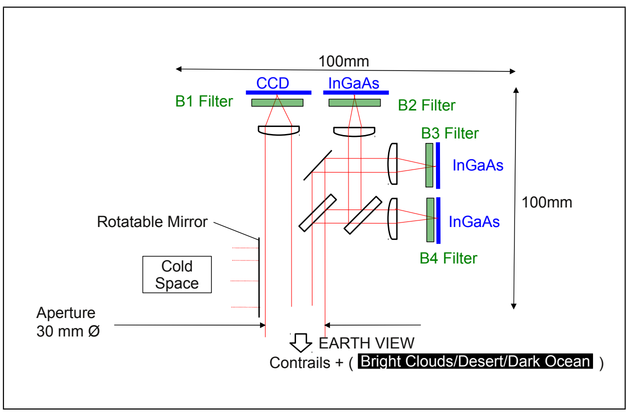

Figure 7. VIR/SWIR Optical Design Description

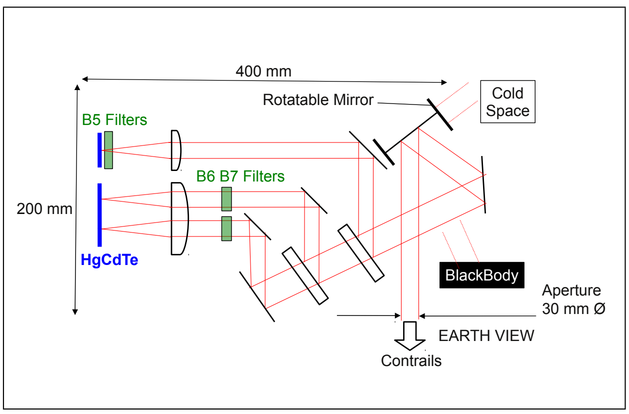

Figure 8. MIR/TIR Optical Design Description

size have ever flown. The Fairchild CCD 143 sensor and an enhancement of the SCIAMACHY EPITAXX InGaAs sensor are fitting the instrument requirements (TRL9).

3.1.3. VIS/SWIR Calibration Description

A rotatable calibration mirror is used in order to provide views (a) of Earth (providing both contrails and bright sources views), (b) cold space. The bright source is provided by the observation of high level opaque clouds, bright deserts or dark oceans for fulfillment of a calibration accuracy better than 5%. The range of bright sources allows to cover the full dynamic range of the instrument. An on-board algorithm ensures the calibration target characterisation [, Govaerts, 2001].

3.1.4. MIR/TIR Optical Design Description

The MIR/TIR system optical design is shown in figure 8. The option to use three separate detectors with separate optics will induce three relatively large apertures, and also have a fairly severe impact on the size of the external calibration hardware. A single aperture and a single detector is therefore preferred, partly for control of system size, but also since a single calibration source and a single detector will likely provide optimum inter-channel relative accuracy. For the TIR, we introduce the dichroics near an intermediate image formed at relatively low aperture, where we have placed the 2 TIR. After exiting the filters, the large intermediate image is imaged onto the detector by a relay lens.

3.1.5. MIR/TIR Sensors Description : Mercury-Cadmium-Telluride (HgCdTe)

The TIR instrument uses a Stirling cycle cooler for maintaining the detectors at 77K, which provides the required radiometer resolution. A slight modification in 2048 x 2048 pixels Teledyne HAWAII-2RG, used in astrophysics, should fit the instrument requirements.

3.1.6. MIR/TIR Calibration Description

A rotatable mirror is used in order to provide views (a) of the Earth (b) of cold space and (c) of a bright black-body. The last two views provide the two known radiance levels that are required for absolute calibration of all MIR/TIR channels. The mirror is used at the same angle of incidence for cold-space and Earth views, so that it has the same emissivity in these two configurations, providing a very good zero radiance reference. Edge structures on the mirror are used to block the cold space aperture during Earth view. The warm Blackbody is a deep-cavity black body, with an emissivity that will always be very close to unity. The Blackbody temperature will be monitored precisely and provide a calibration accuracy better than 1K.

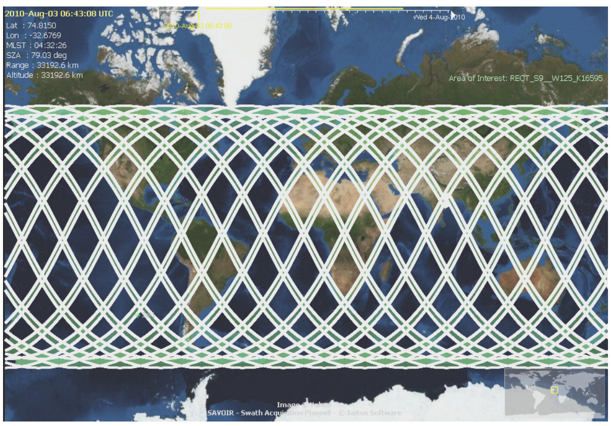

Figure 10. Groundtrack of one satellite.

3.2. Mission Concept

The observational requirements of the mission demand a coverage of the major air corridors in the Northern hemisphere, i.e. Western Europe, the North Atlantic and North America. The area of interest is to be covered between 09:00 and 17:00 local time in a high timely (at least hourly) resolution. In addition, a daily uplink possibility and at least ten downlinks per day have to be provided. To achieve these requirements, non SSO LEO orbits with an inclination of 60° and an altitude of 566 km have been chosen. The groundtrack of one satellite is shown in Fig.10. A constellation of 8 satellites is necessary for the time resolution. These orbits have a time period of 96 min which yields 15 orbits per day. To achieve the desired one-hour revisit time of the constellation, the difference between the ascending nodes of two adjacent orbital planes is 15°. In this configuration the two ground stations Neustrelitz, Germany and Perth, Australia, provide an average contact time of 7min per orbit with a download capability of 25Gbit/orbit.

The Indian PSLV launcher has been selected for this mission. It has a launch capacity of 2200kg to LEO and can accommodate a payload of 2.7m in diameter. This way the constellation can be injected in one single launch by using a circular arrangement of the satellites on a custom built dispenser. As alternatives a Russian DNEPR launcher or a SOYUZ from Kourou can be used, but they would considerably increase the launch costs. For orbit injection, the launcher releases the satellites to a 800km orbit, where the first satellite is immediately decellerated to the target orbit of 566km. The flattening of the earth, which produces a slower drift of the orbit planes in the higher altitude, is used to bring the other satellites to their designated orbits. With a difference in the secular movement of the ascending node of $\Delta\Omega = 0.4°$/day it will take approximately 37.5 days to reach the next target orbit, when the next satellite is decelerated to 566km. This way it takes about eight to nine months to complete the constellation.

3.3. Subsystems

3.3.1. Overall spacecraft design

The basic shape of the ERICC spacecraft is a trapeze with dimensions of 80cm x 50cm x 120 cm. Overall spacecraft mass is 190 kg. Solar arrays are mounted on the zenith surface of the spacecraft and on 3 sides. The payload and radiators are mounted on the nadir looking surface. Various antennas and sensors are distributed over the different surface areas.

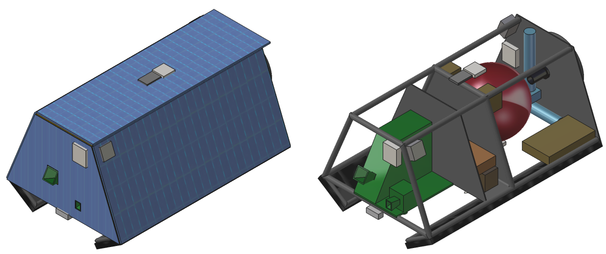

Figure 9. General design of the spacecraft.

3.3.2. Structure

The satellite structure consists of a strong baseplate, a fairing (interface to the launcher) and a lightweight beam structure. For arranging the components inside the spacecraft, special care was taken to ensure that the spacecraft's principal axis of inertia are aligned with the main spacecraft axis and that the CoG is close to the aerodynamic center. Compatibility of components was also considered during the structural layout, so that there is a sufficient distance between critical components like electronic equipment and magnetic torquers.

3.3.3. Thermal Control System (TCS)

The mission imposes some specific challenges to thermal control. In addition to maintaining the components' operating temperature ranges, the MIR/TIR Sensors have to be stabilized at a temperature of 77 K ±5K. The large (solar cell) areas serve as working areas for solar radiation. The non sun-synchronous orbit provides highly alternating illumination conditions over an orbit-year and the only surface not pointing towards the sun for a significant amount of time is the earth-facing side.

The remote sensing payload, the electronics and the batteries were identified as instruments with tightest temperature ranges. A worst-case hot temperature of 40C and a worst-case cold temperature of -10°C were calculated. Thus the temperatures can be controlled by passive thermal control elements, including body mounted heaters, heat pipes and thermal masses as heat sinks and storage. The only active element is a Sterling cooler for temperature stabilization of the MIR/TIR sensors. The battery is thermally isolated, since its maximum operational temperature of 35°C will be exceeded. For the cold case heat sinks, heat stored in the structure and the short eclipse of 35min will assure that the temperature margins will be maintained.

The radiator area was calculated to an area of 0.5^2. They are mounted on the earth facing side of the satellite in order to avoid sun exposure. But radiator surfaces pointing towards the earth are less effective than pointing towards cold space, due to earth radiation. Since the view angle of the earth is 66°, the radiators are inclined by 33° to radiate into deep space.

3.3.4. Attitude Determination and Orbit Control / Propulsion

The main mission requirements for the ADCS subsystem were: nadir pointing with an accuracy of at least 0.02 deg for the payload, a pointing stability of 0.2 deg/sec and an accuracy of attitude knowledge of 10 arcsec. Also a maximum slew rate of 90 deg/min, and an orbit determination with a margin of 200 m. The sizing and selection process, in order to fulfill the requirements ended up with two star trackers and an inertia measurement unit for precision attitude determination. Also two sun sensors, one GPS receiver and a magnetometer were selected for other operational requirements´ compliance. A three axis stabilization option provided the optimal solution, with a typical arrangement of four reaction wheels, and three magnetorquers. The total mass and power allocated for the ADCS subsystem is 19.2 kg and 23.6 W respectively, with only a 5% margin, due to the technology readiness level of the selected components.

The orbit control/propulsion subsystem´ s mission requirements were to perform the final orbit acquisition, maintain the orbit altitude and deorbit the spacecraft at the end of the mission. The total delta V for the above requirements was estimated to about 190 m/s. A reliable monopropellant solution of hydrazine (Isp 220s) was selected considering mission lifetime and mass budget limitations, with a dry mass of about 6 kg (thruster, fuel tank, etc), and an estimated 18 kg for propellant mass.

3.3.5. Energy and Power System (EPS)

Given the fact that the satellite size must remain small, a deployable solar panels option should be avoided. The required power from solar arrays is 270W. For conventional flat panels, a $1.1m^2$ surface would have been sufficient. However, in our case the solar arrays (gallium arsenide on germanium) are set directly on the external walls of the platform. Therefore, the surface must be oversized to $2.25m^2$ in order to compensate for the high variation of incidence angle and surface illumination. The 122 W mean power consumed during eclipse poses a requirement for a 10 Ah battery, with a low depth of discharge (45%). In order to counteract the battery degradation due to the solar panels' configuration, we use a 28V SAFT Lithium-Ion battery with an oversized capacity of 54 Ah. Regarding the Power Control and Distribution Unit (PCDU), a direct energy transfer management has been selected, because the solar arrays' spatial distribution prevents the system from high electrical overloads.

Payload	Mass (kg)	Margin 20%	TRL
Spectral Imager	40	48	8
Bus			8
Structure	48.8	58.6	9
AOCS	41.3	5	9
EPS	22.2	26.6	9
Thermals	7.6	9.12	8 to 9
TT&C	6.5	7.8	9
Onboard computer	2.7	3.24	9
Total bus	129.1	110	
Total system	169.1	158	
System margin		31.6	
Total with margin (20%)		190	

Figure 11. Mass and TRL Budget

3.3.6. On board data handling (OBHD)

The OBHD subsystem includes two on board computers (OBCs) for redundancy and one high speed data recording unit. The OBCs operate in a master-slave configuration. The data recording unit provides fast memory access (150 Mbit/s writing speed) over different channels and data storage of 128 Gbit. To ensure sufficient storage margins, data compression (factor 2) is used.

3.3.7. Telemetry Tracking and Control (TT&C)

The TT&C subsystem is comprised from a primary X-band telemetry downlink, an S-band telecommand uplink and an S-band backup telemetry downlink (housekeeping data only). The X-band downlink provides a data rate of 140 Mbit/s, which allows the data download of one orbit in

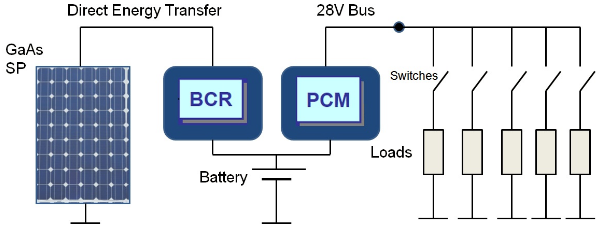

Figure 12. General overview of the EPS (fully regulated bus).

1.5 minutes. For this link, two redundant transmitters with a TX power of 3,5W and a high gain tracking horn antenna is used. The S-band telecommand uplink provides a data rate of 0,5 Mbit/s, using two redundant receivers and two wide beam patch antennas.

4. Conclusion

ERICC is a newly-proposed space mission with great potential for improved understanding of climate change. It is a novel mission, the first to specifically target the climatic impact of contrails, from space. ERICC offers improved capabilities over previous missions and will well-complement other future missions. ERICC incorporate an innovative orbital solution to demanding science requirements and also a solid technical basis - none of the technology involved has a TRL less than 8/9. By careful consideration of trade-offs, we have achieved an excellent balance between our scientific aims, technical feasibility and good value for investment.

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References

H. Mannstein. *Contrail observations from space using NOAA-AVHRR data.*, 2000.

M. Vazquez-Navarro et al. *Automatic tracking of the life cycle of contrails*, 2010.

Airports Council International (ACI) Traffic Forecast Advisory Services. *Global traffic forecast 2006-2025, executive summary..*, 2007.

Penner, J.E., et al. (eds.). *IPCC, 1999: Aviation and the Global Atmosphere: A Special Report of IPCC Working Groups I and III* , 1999.

Foster, P., et al. *IPCC, 2007: WG1,C.2* 2007

Minnis, P., Ayers, J. K., Palikonda, R. and Phan D. *Contrails, Cirrus Trends, and Climate.*, 2004.

Gierens, K., et al. *Ice-supersaturated regions and subvisible cirrus in the northern midlatitude upper troposphere*, 2000.

Ulrich Schumann. *Formation, properties and climatic effects of contrails*, 2005.

Steven J. Cooper et al. *Objective Assessment of the Information Content of Visible and Infrared Radiance Measurements for Cloud Microphysical Property Retrievals over the Global Oceans. Part II: Ice Clouds* 2005.

Ping Yang et al. *Contrails and Induced Cirrus: Optics and Radiation*, 2005

Y.M. Govaerts et al. *Operationnal vicarious calibration of the MSG/SEVIRI solar channels*, Adv. Space Res., 2001