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EARTHQUAKE FORECAST SCIENCE RESEARCH WITH A SMALL SATELLITE

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Abstract. Reliable, repeatable Earthquake forecast is a subject surrounded by controversy and scepticism. What is clear, is that reliable forecast could be the single most effective tool for earthquake disaster management. Roughly a third of the world's population live in areas that are at risk and, every year since the beginning of the twentieth century earthquakes have caused an average of 20,000 deaths. The economic loss in the 1995 Kobe, Japan earthquake was greater than US$100 billion .

Substantial progress has been made on the development of methods for earthquake hazard analysis on a timescale of a few decades. However, the forecast of specific earthquakes on timescales of a few years to a few days is a difficult problem. It has been proposed that satellites and ground-based facilities may detect earthquake precursors in the ionosphere a few hours or days before the main shock. This hypothesis is now backed by a physical model, derived by the Russian Academy of Sciences from statistical studies, and an understanding of the main morphological features of seismo-ionospheric precursors - which allows them to be separated from background ionospheric variability. The main problems now are lack of regular global data and limited funding for what is considered to be financially risky research. Low-cost, small satellites offer a solution to these problems. A 100 kg class SSTL enhanced microsatellite, carrying a RAS topside sounder and complimentary payload, will be used to make regular measurements over seismically active zones around the globe. The low cost of the spacecraft offers a financially low-risk approach to the next step in this invaluable research.

The spacecraft will make ionospheric measurements for systematic research into the proposed precursors. The aims will be to confirm or refute the hypothesis; define their reliability and reproducibility; and enable further scientific understanding of their mechanisms. In addition, forecasting of the magnitude of the events, as well as an indication of the seismic centre may also be possible. These mission data should also lead to improved knowledge of the physics of earthquakes, improved accuracy for GPS-based navigation models, and could be used to study the reaction of the global ionosphere during magnetic storms and other solar-terrestrial events. The paper presents an overview of the scientific basis, goals, and proposed platform for this research mission.

Rationale and Approach

Reliable, repeatable Earthquake forecast on timescales of a few years to a few days is would be a critical tool for Earthquake disaster management. Substantial progress has been made on the development of methods for earthquake hazard analysis on a timescale of a few decades. The forecast of specific earthquakes on timescales of a few years to a few days is a difficult problem, and research continues into all hypothesised correlations between geophysical phenomena and seismic activity[1]. Currently, lack of regular statistical data and clear understanding of the physical coupling mechanisms place these in the realm of speculative science. Should any of these correlations be proven and understood to the extent that they may potentially be used for repeatable short-term Earthquake forecasting, then extensive work will still be required in order to ascertain how reliable the forecasts are. This is vitally important, as unreliable forecast could be equally devastating[2].

Despite huge financial investment into effective Earthquake Disaster Management, little has been invested into Earthquake forecast research. This is most probably due to the difficulty in understanding the complex physics leading to the problem plus the scepticism surrounding this subject as a whole, which renders it a higher financial risk. There are many different theories of observable phenomena that appear to correlate with seismic activity. Most widely publicised and growing in support are thermal, electromagnetic and ionospheric phenomena[1-7]. The prime objective of the proposed mission focuses on investigation of seism-ionospheric coupling, with potential for secondary investigations into seismo-electromagnetic correlations. This will offer some complementarity with the CNES Demeter mission[5].

An effective 'operational Earthquake forecast' would need to stipulate the time, place, and magnitude of the future event, with estimates of uncertainties for each of these parameters[3]. Clearly, the field of Earthquake forecast is immature and is in the early stages of research. The proposed mission aims simply to provide regular statistical data from key seismic regions around the globe, in an attempt to (a) confirm or refute the proposed seismo-ionospheric precursors and, (b) if indications are favourable, the data would be used to adequately define their reliability and reproducibility. Once these are established, it should enable the basis of the precursors to be sought in knowledge of the physics of the Earthquake process. Positive results from this pathfinder mission would lead operational data gathering, ideally via a constellation of low cost satellites, offering high revisit rates for high accuracy modelling. This would be an important stage for establishing the feasibility of repeatable forecast. The final and vital step would then be evaluation of the reliability of Earthquake forecast: although this stage is beyond the scope of this paper.

Seismo-Ionospheric Science

Background

It has been proposed that satellites and ground-based facilities may detect earthquake precursors in the ionosphere a few hours or days before the main shock[8]. A physical model has been derived by the IZMIRAN Russian Academy of Sciences (RAS) from statistical studies, now backs this hypothesis. This model incorporates an understanding of the main morphological features of seismo-ionospheric precursors which allows them to be separated from background ionospheric variability[9]. In addition, to time forecasting, forecasting of the magnitude of the events, as well as an indication of the seismic centre may also be possible by this method.

Further backing that ionospheric perturbations are correlated with seismic activity is also emerging from other groups including the NASDA Earthquake Remote Sensing Frontier Project[4-15].

The Vertical Electric Field as a Source of Ionospheric Variability

Most existing models of seismo-ionospheric coupling acknowledge the important role of atmospheric electricity. Due to the anisotropy of atmosphere conductivity at heights greater than 60 km, the large-scale, high intensity (~ 1000 V/m) vertical electric field appearing at seismically active regions a few days before strong earthquakes can penetrate into the ionosphere and create specific irregularities of electron concentration in this region. Due to high conductivity along the geomagnetic field lines the seismogenic variations in near-earth plasma represent the modification of a magnetic-force tube leaning on area of earthquake preparation by an anomalous quasistatic electric field generated on a surface of ground in a seismoactive zone. This modification is manifested in many physical parameters of space plasma which could be measured onboard the satellite.

Proposed Measurements of Ionospheric Parameters

Based on retrospective analysis of existing satellite measurements of seismo-ionospheric variations and existing models, the following set of measurements ionospheric parameters can be proposed:

- *Density measurements in F-layer maximum (critical frequency)*
- *Measurements of height of F-layer maximum*
- *Measurements of vertical profiles of ionization (both for topside, and bottomside ionosphere)*
- *Measurements of the total electron content (TEC)*
- *Measurements of ion composition*
- *Electron temperature measurements*

To make these measurements regularly over the seismically active zones, a topside ionospheric sounder and complimentary payload will be flown on a 100 kg class SSTL low cost microsatellite. Depending on payload possibilities the measurements of electric and magnetic fields, VLF emissions and energetic particle fluxes could also be considered.

In order to identify variations with local time, global and regional variations, it is critical to ensure that satellite and ground-based measurements are coordinated wherever possible. Ideally, the mission would be organised in such a way that data are processed in practically real time and would be available to a broad sector of the scientific community. The exchange of satellite and ground based measurements data should be provided, especially with establishments conducting ionospheric measurements: ground based vertical ionosondes, IS radars, GPS receivers providing the GPS TEC data. Coordination with the seismic network and network providing the atmospheric electricity, radon measurements and aerosols should also be organized. Such close cooperation of ground based and satellite measurements should dramatically improve our understanding of the physical mechanisms of seismo-ionospheric coupling.

Other Earthquake Forecast Science Research Missions

Currently the DEMETER (CNES), VULCAN (RSA) and WARNING (Lead by the University of the Ukraine) missions are baselined to make measurements to support earthquake forecast research.

The WARNING mission has been under study for many years and work continues. The VULCAN mission has numerous objectives; with Earthquake forecast research as one of them. Therefore regular, dedicated measurements over seismic zones will not be possible.

The prime objectives of the DEMETER mission are to study the disturbances of the ionosphere due to seismo-electromagnetic effects and due to anthropogenic activities[6]. One of the secondary goals will be to make measurements of the electron density disturbances over seismic zones – namely observing variations in critical frequencies in different regions of the ionosphere and TEC measurements. Therefore, it can be seen that DEMETER and the proposed Earthquake Forecast science research (EQFS) mission are largely complimentary – with EQFS providing more extensive measurements of seismo-ionospheric variations, with a possible secondary objective to investigate VLF emissions. Ideally both missions should provide additional comparative data to each other.

Other Applications of the Topside Ionospheric Data

In addition to HF radio transmissions (commonly used in tactical military communications) being very dependent on the state of the ionosphere in communications, there are numerous other applications that are affected by the ionosphere and its interactions. The introduction of regularly acquired topside ionosphere data could offer significant enhancements to models and model accuracy in many of these areas[14].

An increasing number of military, commercial and civilian navigation applications are based on GPS technology. However, the precision of this is affected by the ionospheric delay: current models do not provide good representation of the global vertical distribution of ionisation in the topside of the ionosphere nor on the shape of the topside profile. The topside sounding measurements obtained through this mission should enable significant improvement in the accuracy of these models. This mission would therefore significantly benefit existing communities using GPS to provide navigation, as well as new projects such as the European Galileo project.

Topside sounding of the ionosphere may also be used to study the reaction of the global ionosphere during magnetic storms and other solar-terrestrial events. It could become a very powerful support to other Space Weather dedicated projects such as TIMED, adding to thermospheric parameters measured by the project, the ionospheric ones.

Pathfinder Mission Concept

An orbit altitude between 800 to 1000 km is baselined for measurements of the topside ionosphere. A high inclination orbit (~ 70° to 85° inclination) will allow global coverage. The higher the temporal frequency of the measurements for the pathfinder mission the better. Taking into account the spatial scale of the modified ionosphere region[8] which is of order 30° in latitude and longitude for strong earthquakes, one satellite will provide at least two passes over the seismically active zone (ascending and descending pares of the daily orbits). Additionally, the seismo-ionospheric variations could be registered on two neighbouring orbits separated by ~25° one from another - so up to 4 passes per day will be possible for the given seismic zone. The data should also be gathered over an extended period to acquire sufficient, reliable statistical data. A two year mission lifetime is targeted to provide some continuity in the collected data.

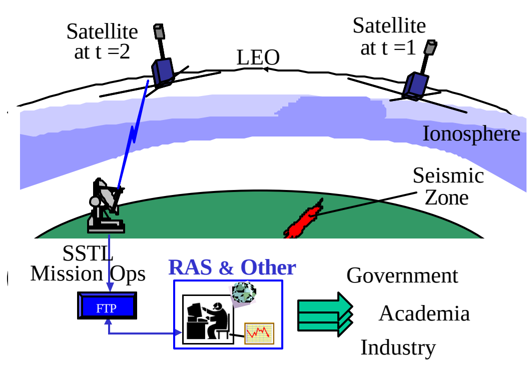

Figure 1 Mission Concept

The main goals of the pathfinder mission are to investigate seismo-ionospheric anomalies in order to attempt to confirm the existence of such relationships as a small step towards operational earthquake forecast.

Spacecraft Design

SSTL Technology Snapshot

The low cost pathfinder mission is based on SSTL's current suite of technologies. One key advantage of the SSTL smaller, faster, cheaper design philosophy is the ability to exploit new technologies as they emerge. This ensures that customers investing in this mission or into the planned constellation can be sure of solutions that capitalise on the advancing technological market.

Recent technological advances at SSTL have been in nanosatellite technology, resulting very capable systems that command low mass and power from subsequent platforms. Additionally, many SSTL platform solutions are evolving towards a common bus that may be used for constellation launches. The timing of this is pertinent as an increasing number of customers wish to exploit low cost small satellites to implement cost-effective constellations of small satellites

Mission Payloads

The payload complement is used, primarily to measure variations of ionospheric electron density distribution with altitude during specific local time intervals over seismic regions in order to look at when a quake might occur on a timescale of days. The Russian Academy of Science has already invested heavily in producing the necessary seismo-ionospheric physical models, and could lead coordination of the data analysis.

Electromagnetic compatibility and spacecraft charging issues must be considered in detail. Knowledge acquired on the Cosmos 1809 and ISIS missions will be exploited to ensure that a suitable low cost solution to these problems may be found.

Table 1 Strawman Payload Characteristics

Strawman Payload	Mass (kg)	Power (W)	Data Rate
Topside Sounder	10	5 (av.) 30 (peak)	~ 2 Mbps
Mass Spectrometer	~8	~20 (av.)	~ 2 kbps
Magnetometer	5	3 (av.)	~ 5 kbps
Subtotal	23	28 (av.) 53 (peak)	~ 2 Mbps
Margin 10 %	2	3 (av.) 5 (peak)	
Total	25	31 (av.) 58 (peak)	~ 2 Mbps

Table 2 Strawman Payload Accommodation

Strawman Payload Accommodation	Comment
Topside Sounder	• Antennas: 15 m tip-to-tip >5 MHz 50 m tip-to-tip < 5 MHz • Main antenna configuration options: - 3 orthogonal dipoles - 2 V-shaped dipoles - 2 crossed dipoles
Mass Spectrometer	• Mounted on platform, inlet directed along the satellite velocity vector
Magnetometer	• Deployed on boom of at least 2-4m to minimise disturbances from the spacecraft

The proposed payload complement is given in Table 1. The topside sounding antennas are mounted on the Earth-facing facet of the spacecraft. The mass spectrometer is mounted so that the inlet is directed on the satellite velocity vector. Finally, the magnetometer is deployed on an instrument boom, which is mounted on the space-facing facet (see Figure 3 in the next section). More details on preliminary payload characteristics and spacecraft accommodation are given in Table 1 and Table 2.

EQFS Platform

The platform supporting the mission is a 100 kg class SSTL satellite. Also, within this platform class are the Topsat and the international Disaster Monitoring Constellation (DMC) satellites. Topsat, (jointly funded by the BNSC and UK MoD) and the first 3 of the DMC satellites are currently under construction at Surrey and many elements of these satellite designs are drawn upon in the EQFS spacecraft design. The major differences between the EQFS and DMC mission platform is the inclusion of an instrument boom (also used for gravity gradient stabilisation) instead of a gravity gradient boom and reduced attitude determination and control requirements. The payloads already have a 10% margin included, but as many of the masses are based on existing flight hardware it should also be possible to use some of the platform contingency for payloads, should this be necessary.

Table 3 Preliminary Mass Budget

Subsystem	Mass (kg)
Structure	16.0
On-board data handling	5.3
Power	23.5
AODCS	11.2
Communications	8.6
Environmental	2.0
PLATFORM SUBTOTAL	66.6
MARGIN 20%	**13.3**
PLATFORM TOTAL	**79.9**
Payload	**25.0**
TOTAL	**104.9**

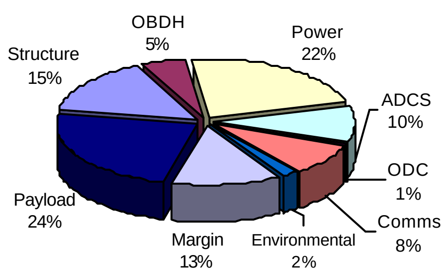

Figure 2 Breakdown of Spacecraft Mass by Subsystem.

The platform mass breakdown is given in Table 3 and is illustrated by subsystem in Figure 2.

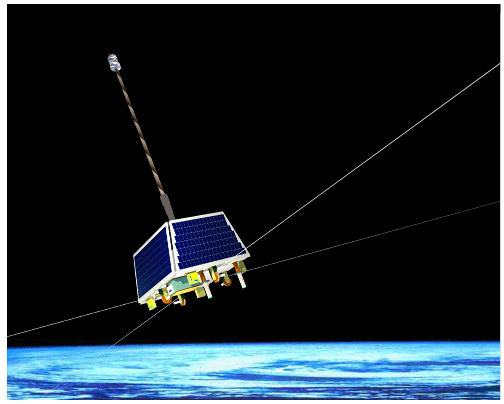

Figure 3 Spacecraft Concept Drawing

Communications

The RF system employs S-band uplinks and downlinks for uploading commands and receiving spacecraft telemetry and payload data.

Payload data is downloaded via an S-band link, which can support data rates up to 2Mbps. Two cold redundant transmitter units, each with its own quadrifilar helix antennas are baselined for this mission. Higher data rate options are available and their impact on mission mass, power, cost and schedule can be determined, should this be required. A 9.6 kbps S-band uplink is used for commanding the spacecraft. Two hot redundant receiver units, each with two patch antennas are baselined.

The transmitter and receiver units are evolved and re-packaged versions of the modules flown on the SSTL SNAP-1 nanosatellite. It is proposed that two receiver patch antennas will be mounted on the Earth and space facing facets of the spacecraft to provide omni-directional coverage, so that communications are possible in any uncontrolled attitude mode.

Power

The power system is based on the battery bus, maximum power point tracking topology, used on all previous SSTL missions. This is particularly suited to low Earth orbit missions. The battery is made up of SANYO Cadmica N-series commercial cells. These will undergo the SSTL screening process is employed on all subsystems including those built for ESA and the USAF[16].

The solar arrays will be made at SSTL using the solar panel integration facility that SSTL has acquired from EEV.

Table 4 Preliminary Power Budget

Subsystem	Total Power (W)
On-board data handling	3.88
Power	1.00
ADCS	3.80
ODC	3.50
Communications	10.85
Payload	**7.75**
SUBTOTAL	**30.78**
MARGIN 10%	**3.01**
TOTAL	**33.90**

For the EQFR demonstration mission the preliminary power budget shown in *Table 4*. The budget is based on 100% duty cycles for power, communications uplink, core OBCs and attitude determination sensors and momentum wheel. GPS and ADCS magnetic actuators are assumed to have a 50% duty cycle, which is above the typical values seen in orbit. The payloads and data downlinks are assumed to have a 25% duty cycle which is in excess of the baseline operating cycle (and which will readily include activity due to the inclusion of an additional ground station for example). With 10% contingency added, and the 'worst case' scenario described above gives roughly a 34 W power requirement. This can nominally be met for the baseline orbit, with 19% efficient cells and an 85% efficient power system. Should higher power be required, higher efficiency cells may be employed.

Higher cost options for increasing platform power, should this be required, might include deploying or extending the panels.

ADCS and Orbit Determination

The platform will be 3-axis stabilised using a boom, magnetorquers and a wheel as actuators. Two wheels are baselined. These may be in the same axis or flown orthoganally depending on the payload-specific requirements. The wheels may be operated in wither reaction or momentum bias modes. These actuators will provide 1 to 2° control (1σ) in all axes, which is ample for the baseline mission payloads. Sun sensors and magnetometers provide attitude determination knowledge to ± 0.5° (1σ) in all axes. The boom will also house the magnetometer payload. All ADCS sensors and actuators in the baseline have been flown in-orbit on previous SSTL missions. The topside sounder antennas will be deployed using a pyrotechnic mechanism that will release each spring-loaded antenna.

A SSTL GPS receiver will also be flown which, without selective availability, enables orbit position determination to 15 metres.

On Board Data Handling

The primary on-board computer is a re-build of the SSTL OBC386 currently in-orbit on the UoSAT-12 minisatellite and being used on the Topsat and DMC missions. The OBC is responsible for TTC tasks as well as running ADCS software. It can also be used to store commands for the payload and would pass them on via the dual redundant Control Area Network (CAN). The CAN network is the primary information exchange mechanism on-board the spacecraft. Most modules are equipped with an off-the-shelf CAN node which can relay telemetry and receive telecommands either from the OBC or directly from the receivers and transmitters.

Assuming a single ground receiving station, with potentially 3 to 5 passes over the station per day, the sounding information gathered over a day would need to be stored in the onboard memory and downlinked during ground station passes. There will be two data recorders, each capable of storing 128 Mbytes of payload data read in from the payloads at just over 2 Mbps. The data recorder may be software upgraded in orbit to offer the same flight software as the primary OBC, thus offering operating redundancy. Up to 0.5 Gbyte per data storage unit is possible, should this be required.

Preliminary Data Budget

This preliminary data throughput analysis assumes that the SSTL Mission Operations Centre is the only ground station. At a payload data rate of approximately 2 Mbps, 16 minutes worth of data can be stored in the 256 Mbytes total memory on-board the satellite.

The transmission time for downlink of an ionogram is determined by its volume and format. So, good coding and information compression is required in order to store and download as many ionograms as possible per orbit. In order to further increase the measurement capacity over an orbit, it may be possible to use additional ground stations to receive payload data. Operational missions may also wish to invest in downlinks supporting higher data rates.

Optional Upgrades

Performance upgrades are available cost options, but it should be noted that selection of some of these may also impact the schedule.

Some increased performance options are:

- Increased data storage
- Higher data downlink rate
- Potential for one or two small additional payloads
- Propulsion system for constellation missions

The mission concept described in this paper represents a trade between performance and keeping the cost low for the research mission. As performance is continually improving, cost effective mission solutions will naturally also evolve with time.

Constellation Concept

Should preliminary results prove positive the next step would be to acquire more accurate results over a suitable period to confirm that these are reliable data.

This would be demonstrated by a suitable constellation of satellites. Some suitable options would be:

- 3-4 satellites at 600-1000 km altitude distributed in longitude. These would study ionospheric precursors only
- 3 satellites at 1000 km altitude orbit to detect ionospheric precursors plus 3 satellites in a 400-600 km altitude orbit to detect electro-magnetic precursors

These would provide higher revisit times and increased data for statistical analysis. The main result should be more accurate data with which to validate the models. In context, this phase should lead to sufficient understanding of the seismo-ionospheric and confirmation of repeatable earthquake forecast and mechanisms. The final stage would then be to establish boundaries for reliable earthquake forecast.

The number of satellites required for an EQFS constellation is determined by the duration of the ionospheric precursor. As shown by the ground based ionospheric measurements[21,22], the mean duration of the ionospheric precursor is approximately 4 hours. Taking into account the ascending and descending passes of the satellite, 3 spacecraft are able to provide the coverage of all local times. In order to enable some overlap in the measurements, 4 satellites would be preferable.

Ideally there would be several receiving stations located in countries that are susceptible to seismic activity, such as Mexico, Chile, Taiwan, China, Italy, Greece, Turkey, and Indonesia. This would enable rapid downloading of the ionograms to the areas at risk and would also free the on-board memory for acquisition of further measurements.

The constellation spacecraft would typically require propulsion systems for on-orbit station acquisition and potentially for small altitude maintenance burns. The proposed baseline for the pathfinder mission may be configured to accommodate a small propulsion system. A system based around 1.1 litre tanks containing xenon propellant pressurised to roughly 60 bar is baselined. Each tank provides up to 3 m/s delta-V and several such tanks could be accommodated on the EQFS platform.

SSTL is currently working on a constellation of satellites capable of providing images of any point on the globe on a daily basis. This will be dedicated to disaster monitoring and is currently under construction at the SSTL facility in Guildford. This experience in cost-effective constellation construction, coordination and operation will significantly benefit such subsequent constellation-based missions.

Programmatics

The target ROM cost for the proposed pathfinder mission *is* ***5.5 million GBP*** at the time of writing**.** This figure *excludes* launch cost and payload development costs, but *includes* the 100 kg class platform, payload interface costs, launch interface costs, launch campaign and two years of operations from the Surrey Mission Operations Centre.

SSTL is expert at sourcing low cost launches and is confident that a suitable low cost launch can be arranged for the EarthQuake Forecast Science Research Mission. The estimated time from mission kick-off to launch-readiness is 18 to 24 months.

Conclusions

It is clear that unreliable EQ forecast could cause considerable damage and the following steps have therefore been proposed to ensure that a logical stepwise approach is adopted. This approach starts with the proposed pathfinder mission for proof of concept

The pathfinder mission aims to characterise and monitor the proposed seismo-ionospheric precursors through regular measurements on a global-scale. Up to now we have data only from older non-dedicated missions. The model was based on measurements from different satellites, and parameters used in the model not always were measured on the same satellite. The main shortage of the previous missions was not continuous measurements. It means that the reliable statistics for seismo-ionospheric phenomena couldn't be built basing on the data of previous missions. So, in addition to the model validation one of the main tasks of the pathfinder mission will be realisation of continuous monitoring regime for statistical studies of space-borne ionospheric precursors of strong earthquakes The data should also lead to improved knowledge not only of the physics of earthquakes but plus improved accuracy for communications, GPS-based navigation models and studies of solar terrestrial events.

Just a quick search on the web will show widespread and extensive debate, hypotheses and analysis on this controversial subject – reflecting huge amounts of thought, effort and money that have already been indirectly invested in this subject[17-20]. Perhaps small direct investment could be used more effectively to explore this route until enough data is gathered for a conclusion to be reached either way.

The low cost mission concept proposed in this paper offer a real and practical opportunity to take a valuable step towards minimising the huge economic losses incurred and to reduce the loss of life, suffering and upheaval that must be borne every year due to Earthquakes. On average, since the year 1900, over 20,000 lives have been lost to Earthquakes on this planet every year.

Earthquake Forecast: Yes Or No?

Yes, Earthquake Forecast is a difficult and potentially dangerous subject. Yes, it is imperative to be sure of results and models. No, this cannot be accomplished by speculating and theorising alone. Yes, more data is needed to be able to conclude *either way*. Yes it can be done at very low cost. Yes, there is a clear way forward if we choose to take it. Are we right to say no?

About the Team

Please contact us if you can contribute to this mission financially, scientifically, technically or, simply to give your support.

SSTL

SSTL has launched 19 spacecraft that have supported Earth observation, space science, communications and technology demonstration missions. Customers include ESA, NASA, the UK MoD and the USAF. SSTL is currently collaborating with the BNSC and international partners to launch a Disaster Monitoring Constellation of satellites which offer global daily revisit at medium resolution.

For more details please see the SSTL website at www.sstl.co.uk

RAS

Institute of Terrestrial Magnetism, Ionosphere and Radiowave Propagation of RAS has participated in many space missions from the very beginning of satellite era. Among the last missions the Intercosmos-19, Cosmos 1809, Bulgaria 1300, APEX (Intercosmos 25), CORONAS-I and CORONAS-F satellites could be mentioned. It is leading institution in Russia in ionospheric studies, especially from onboard the satellites. The first digital ionospheric sounder was launched by IZMIRAN in 1978 onboard Intercosmos-19 satellite (antares.izmiran.rssi.ru/projects/IK-19). Institute has wide cooperation with NASA, CNES, Ukraine NSA, and ESA.

For more details please see the IZMIRAN website at http://www.izmiran.rssi.ru./

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