

Microsatellite Ionospheric Network in Orbit

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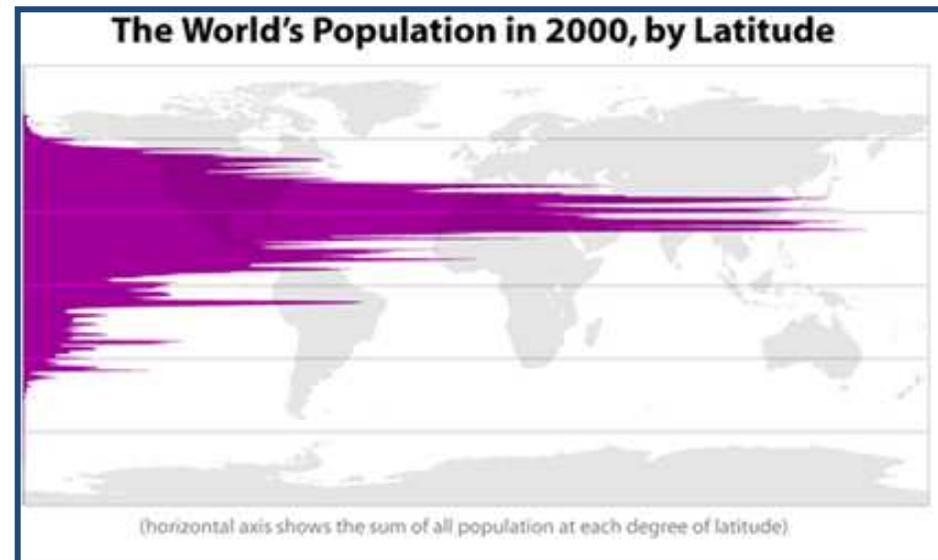
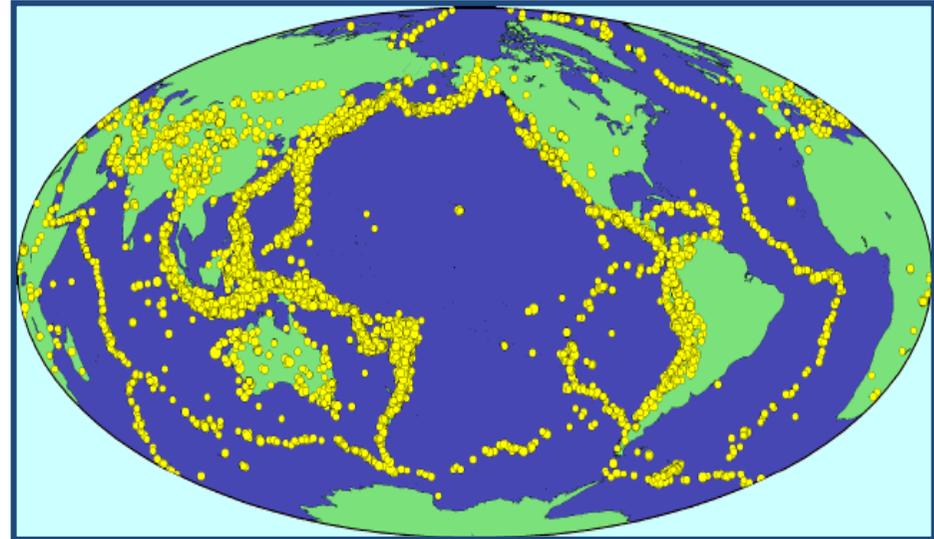
In tribute to Mino Freund
1962- 2012

Introduction

- **Objective**
 - To propose a multi-satellite constellation that could provide adequate warning of impending earthquake events
- **Talk structure**
 - A brief discussion of the risk
 - Possible precursor mechanisms
 - Evidence for the selected precursors
 - Payload instruments
 - Platform concept
 - System concept
 - Conclusions and outstanding questions

Where is the risk?

- Earthquakes occur on a global basis
- They most frequently occur on plate boundaries
- Clearly, though, the Earth's population lives between 60° N and 60° S
- Any satellite constellation should be designed to cover this band of latitudes



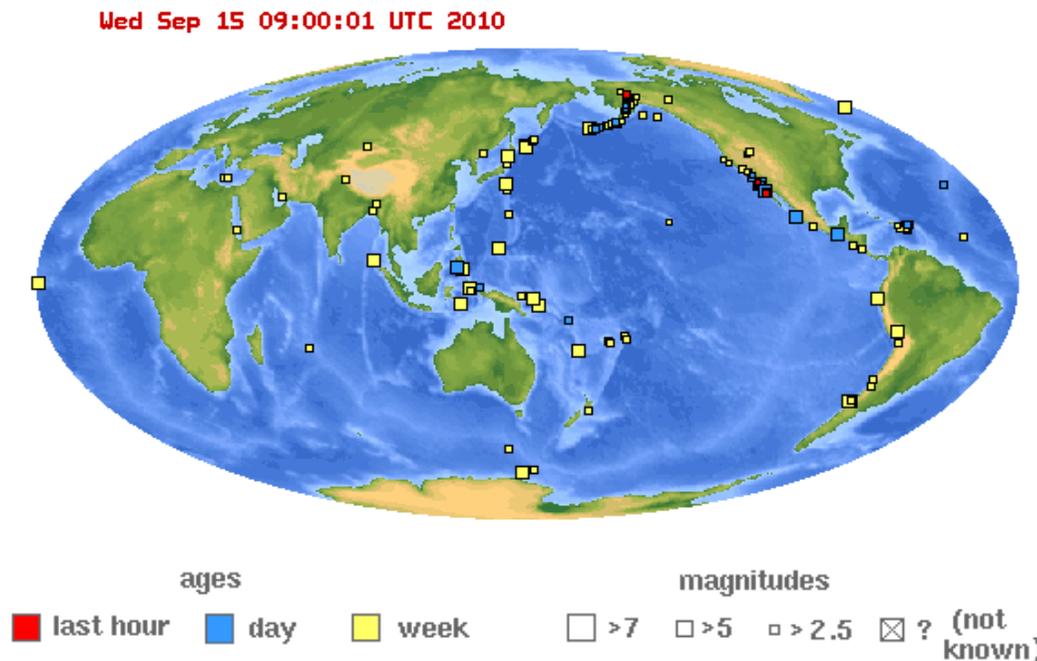
Where's the risk?

- Pseudotachylites veins are formed by frictional melting of the wall rocks during rapid fault movement
- They indicate significant but less frequent risks exist in regions well away from identified plate boundaries, such as the New Madrid zone on the Mississippi
- Monitoring needs to cover these regions too.....



How frequent is the risk?

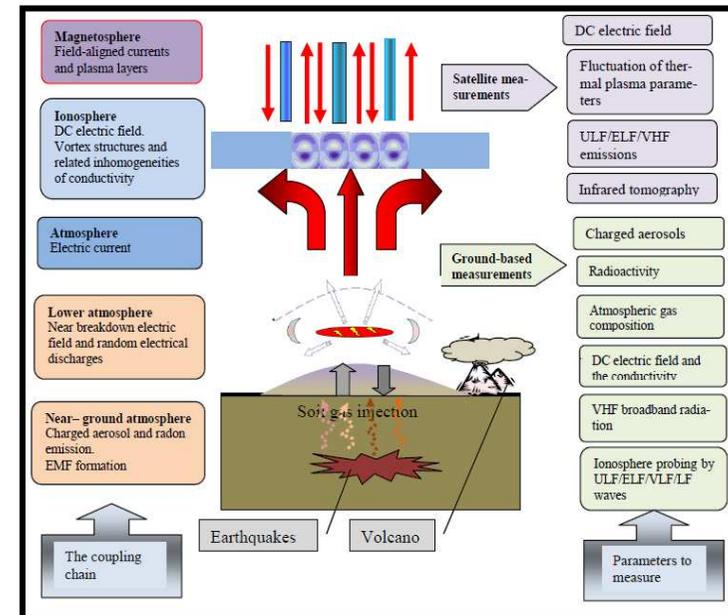
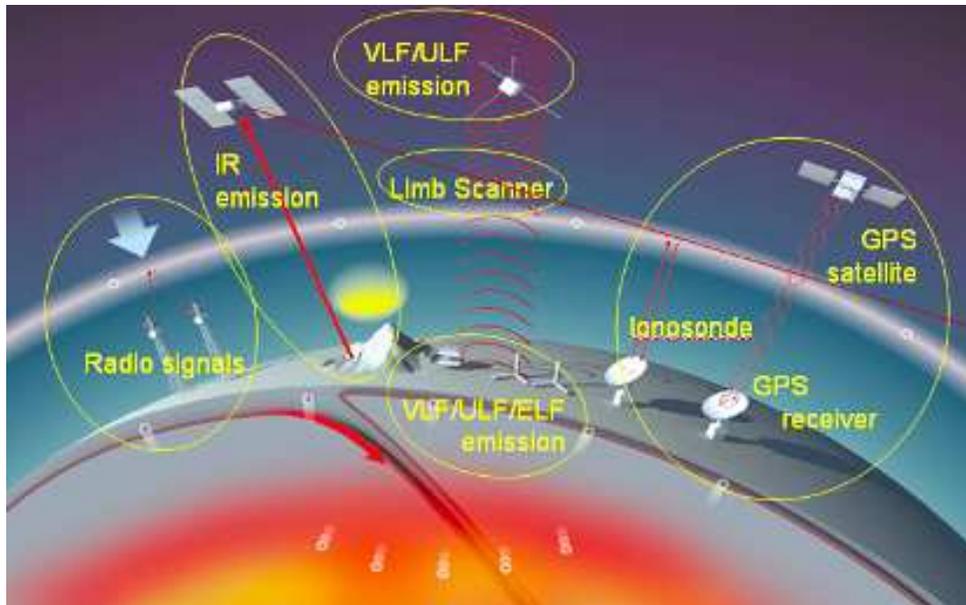
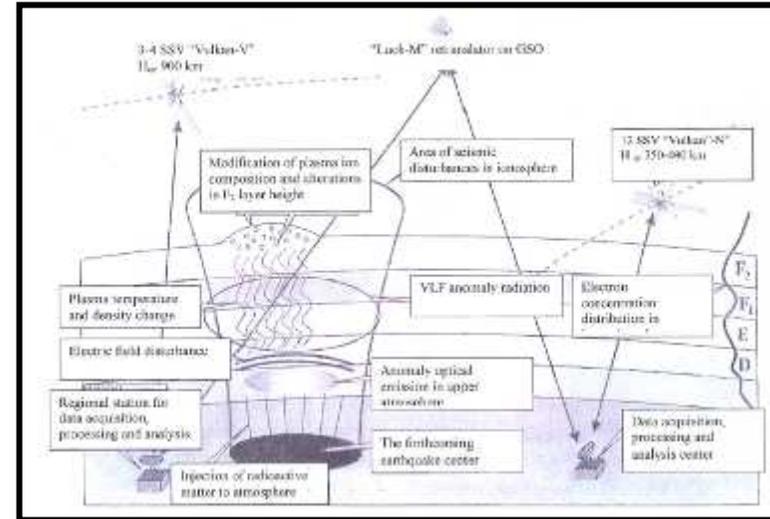
- USGS indicates ~1500 earthquakes a year worldwide with magnitude > 5
 - ~5 per day (on average)



- A multiple-satellite constellation with automated data processing appears indicated to cope with the expected volume of events

Physical Precursor Mechanisms

- There is considerable debate concerning the physics that may create observable precursors
- But there is increasing agreement that there are precursors





Effective Event Prediction

- Government agencies require a reliable prediction system with an associated measure of confidence
- Ideal prediction consists of timely prediction in three areas:
 - *Temporal* – accurate forecasting of when an event will occur
 - *Spatial* – prediction of the epicentre of the event and its spatial extent
 - *Magnitude* – how powerful the principal earthquake event will be
- The inherent variability in these elements still needs to be established
- Correlation of more than one precursor measurement could provide greater levels of certainty

Potential Precursor Phenomena

- Release of radon gas at the Earth's surface
- Light pulses emitted at or near the surface
- “Thermal” fluctuations of the order ~2-10K
- Atmospheric pressure/humidity anomalies resulting extremely localised weather phenomena
- Production of low frequency electromagnetic waves
- Changes in the Total Electron Content of the Ionosphere



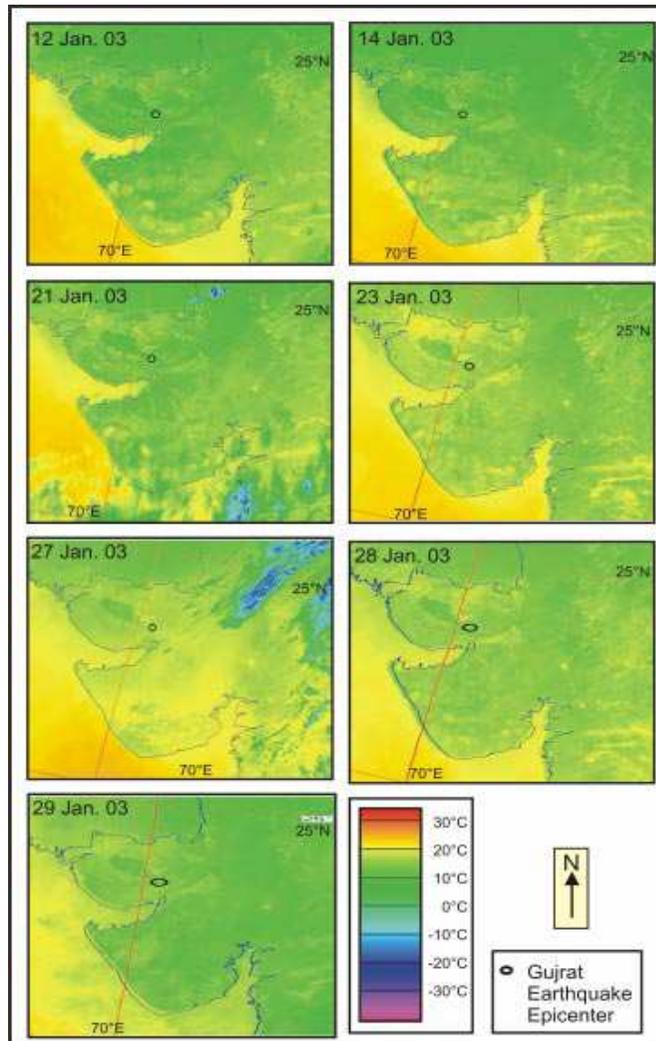
Earthquake lights photographed by T. Kuribashi during 1966 Matsushiro earthquake swarm, Japan

Of these possible precursors:-

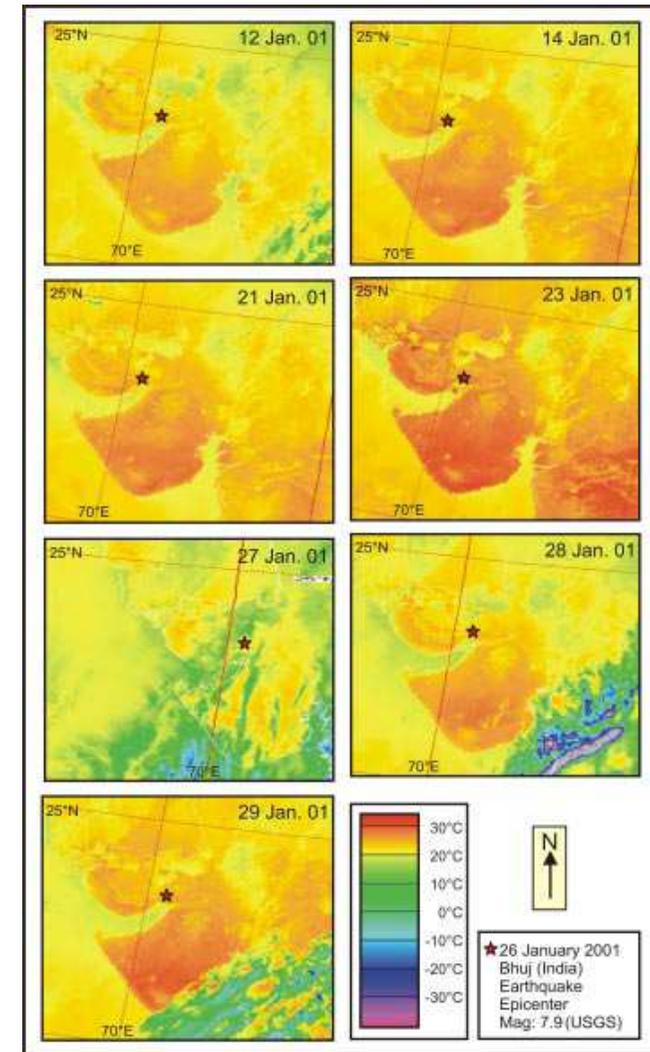
- variations in the ionosphere
- thermal fluctuations appear to be detectable and offer up to a week's warning

“Thermal” Precursors

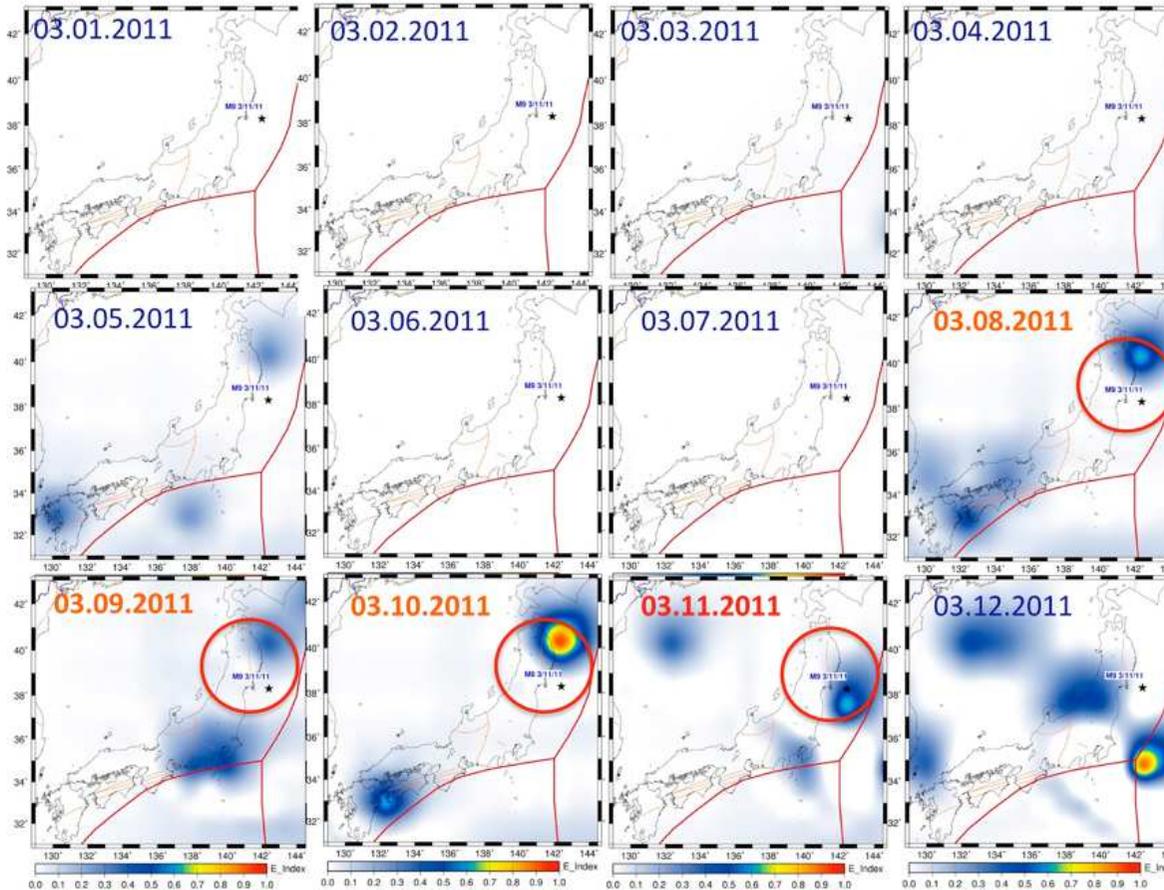
Land Surface Temperature (LST) maps showing Nominal thermal characteristics of the Gujarat, Bhuj, India.



Maps prior to the earthquake of 26 January 2001 in Bhuj, India. Thermal anomaly appeared on 14 January and was maximum on 23 January.



“Thermal” Precursors



The air in the vicinity of the earthquake zone is ionised

Water molecules are attracted to ions in the air, ionisation triggers the large scale condensation of water.

The process of condensation also releases heat and it is this that causes infrared emissions

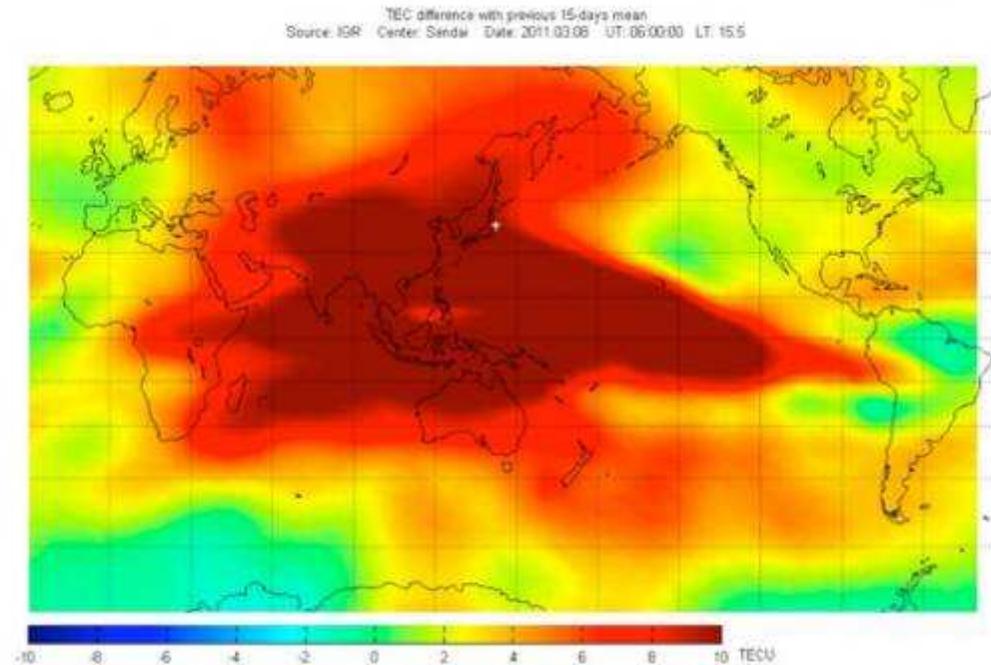
Tohoku M9 Earthquake March 11, 2011

Dimitar Ouzounov - NASA Goddard

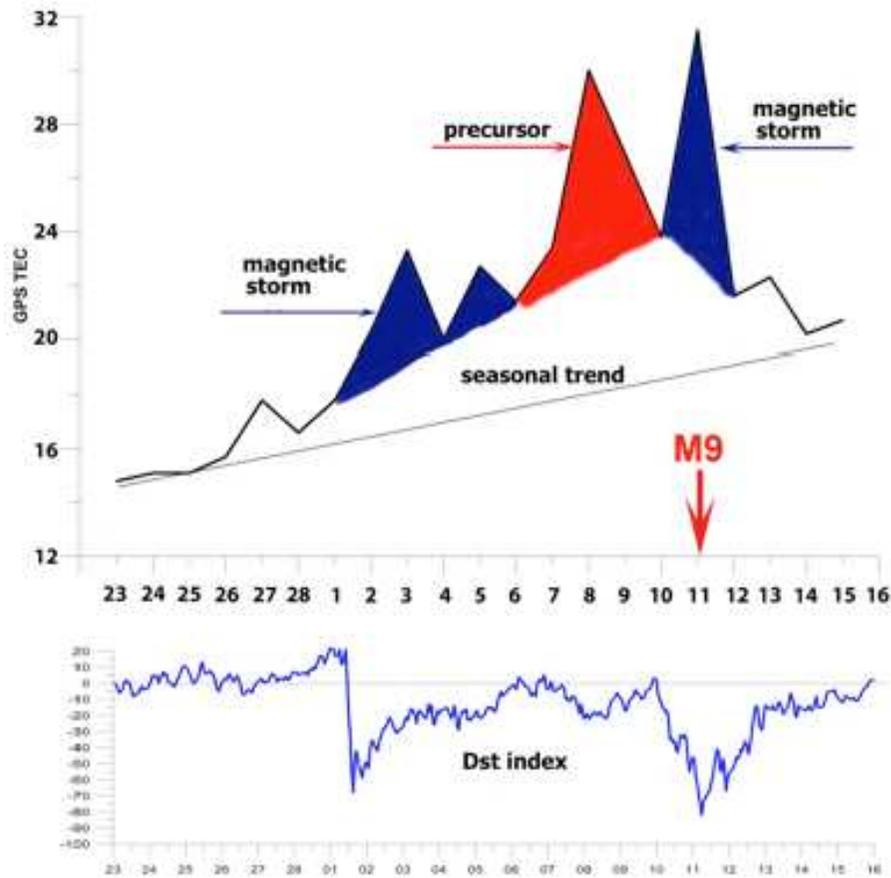
Time series of daytime anomalous OLR observed from NOAA/AVHRR (06.30LT equatorial crossing time) March 1-March 12, 2011. Tectonic plate boundaries are indicated with red lines and major faults by brown ones and earthquake location by black stars. Red circle show the spatial location of abnormal OLR anomalies within vicinity of M9.0 Tohoku earthquake.

Ionospheric Precursors

- The Total Electron Content of the ionosphere 3 days prior to the Tohoku earthquake, (compared to the previous 15-day mean)
- The evidence of “a precursor effect” would seem indisputable, but it would be hard to argue that it offers a reliable indication of location



Tohoku M9 Earthquake



(Dst: Geomagnetic Disturbance storm time)

Time series of GPS/TEC variability observed from Feb 23 to March 16, 2011 for the grid point closest to epicenter for the 15.5 LT (top); and the Dst index for the same Period (bottom). The Dst data were provided by World Data Center (WDC), Geomagnetism, Kyoto, Japan.

Candidate Thermal Sensor

- SSC/SSTL Microbolometer
- Two commercial-off-the-shelf (COTS) un-cooled microbolometer arrays in a push-broom configuration
- Two wavebands
 - MIR (3 μ m to 5 μ m)
 - TIR (8 μ m to 12 μ m)
- Noise equivalent temperature difference (NETD) for a 300 K ground scene = 0.4K
- GSD = 300 m
- Swath = 100 km
- Unit Length ~14cm
- Unit Flight Mass ~2 kg



Bench prototype TIR sensor



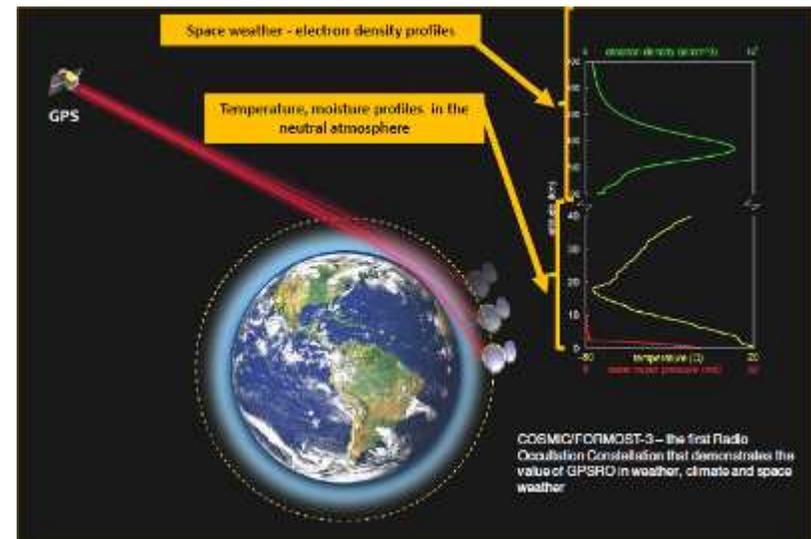
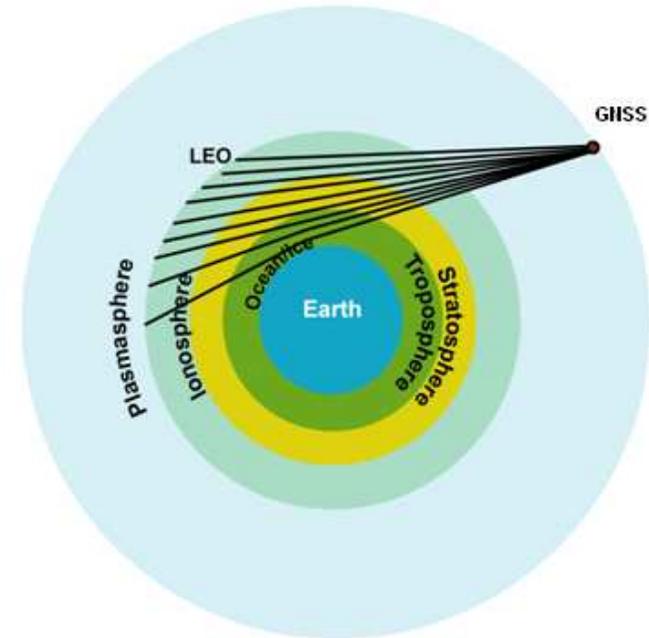
6-sensor array
to provide
600km swath

SSC/SSTL Microbolometer

| Detector Array Parameter | Value |
|----------------------------|---------------------------------------|
| Model Name | UL 01 01 1 |
| Manufacturer | ULIS (Grenoble, France) |
| Detector Type | Microbolometer Detector Array |
| Detector Material | Resistive Amorphous Silicon |
| TCR of detector material | 2.5 % K ⁻¹ |
| Design Waveband | 8 – 14 μm |
| Pixel Count | 240 × 320 |
| Pixel Pitch | 45 μm × 45 μm |
| Fill Factor | > 80 % |
| Sensitive area | 11.4 mm × 10.8 mm |
| Responsivity (mV/K) | 4 mV K ⁻¹ |
| Peak Responsivity (W/K) | 7 × 10 ⁶ V W ⁻¹ |
| NETD @ 300 K w/ f/1 optics | < 120 mK |
| Thermal time constant | 4 ms (-3 dB cut-off) |
| Frame Rate | 50 – 60 Hz (5.5 MHz clock) |
| Rms noise | 480 μV |
| Dynamic Range | 60 K (-10° C to + 50° C) |
| Power Consumption | < 200 mW |
| Weight | < 50 g |
| Cost | € 10,000 |

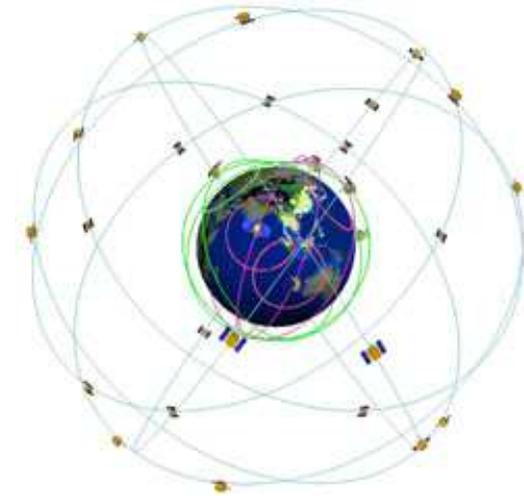
GNSS Radio Occultation

- Detecting effects in the ionosphere using GNSS occultation techniques
- Dual band receivers can be used to detect both the total electron content and short-term scintillation effects
- The Cosmic-1/Formosat-3 constellation demonstrates what could be achieved

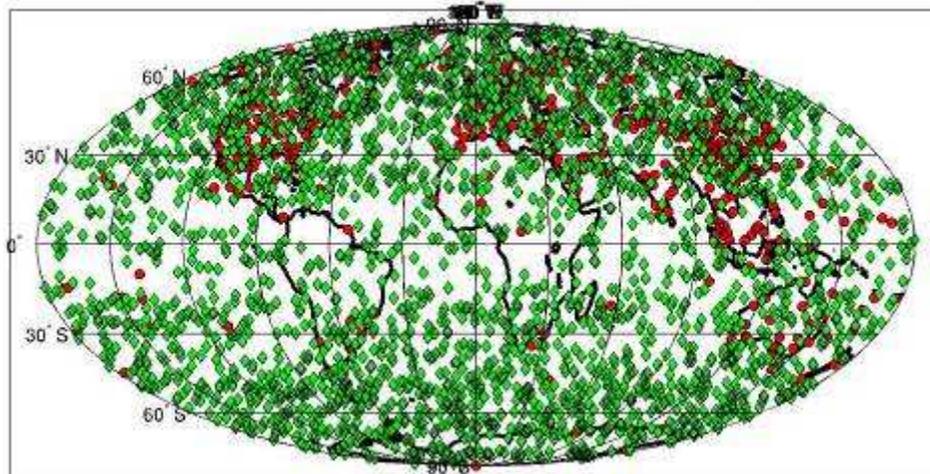


Analogous to COSMIC-1/FORMOSAT-3

- Unprecedented spatial and temporal coverage will be possible using both GPS and Galileo for occultation measurements
- MINO will also provide better models for meteorology, ionosphere and climate change.
- Significant improvements in “data void regions” in weather forecasting
- GNSS Radio Occultation provides superior vertical resolution compared to conventional sounders



Occultation Locations for COSMIC, 6 S/C, 6 Planes, 24 Hrs

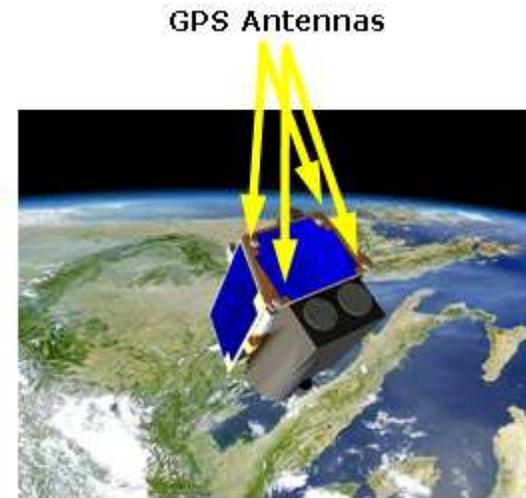


Additional Data Applications

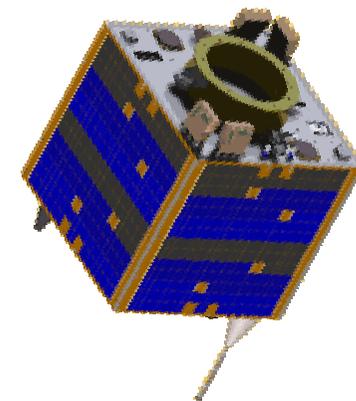
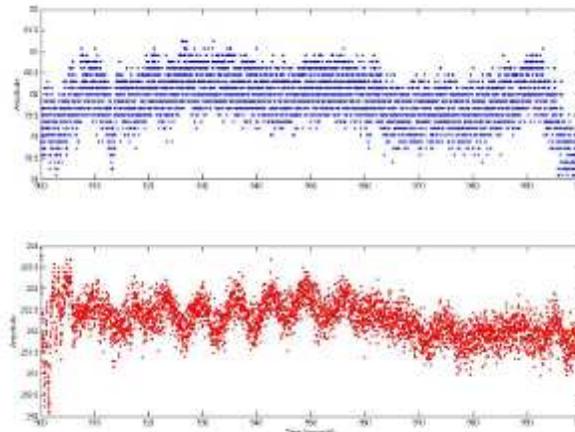
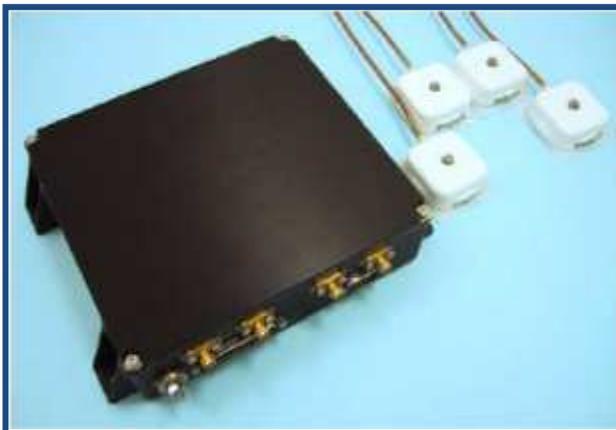
- Medium range (3-15day) weather forecasting
- Typhoon / Hurricane path prediction
- Climate modelling
- Space weather forecasting

Poise Experiment

- Originally conceived as a scintillation measurement experiment by a UK school who won a competition to put an experiment on an SSTL spacecraft
- SSTL's SGR GPS receiver modified to fly algorithms to sense and record scintillation events on TopSat
- Currently using existing SGR-10 receiver on UK-DMC2 to measure scintillation using GPS signals



TopSat

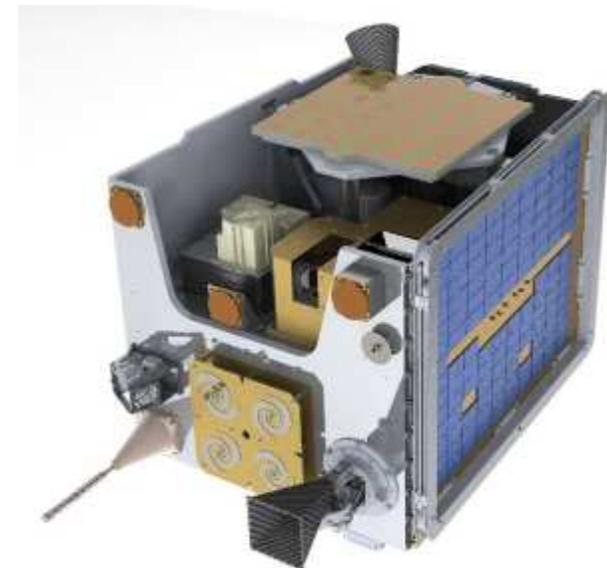
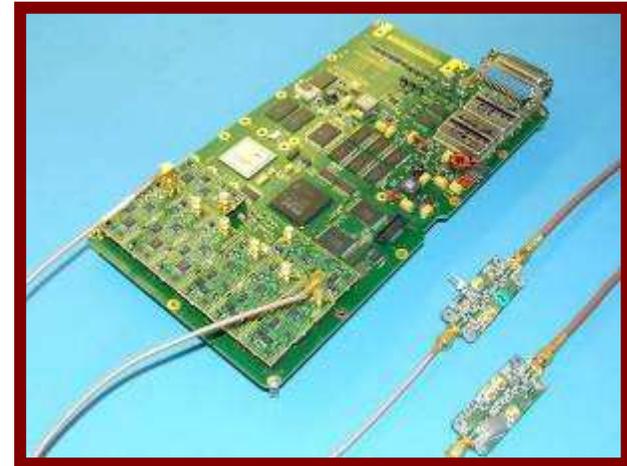


UK-DMC-2

SGR-ReSI Capability

- SSTL developing new generation of GNSS receivers
 - GNSS: GPS, Galileo, Glonass, EGNOS/WAAS
 - Dual frequency, (L1 & L2C), new wider BW signals
 - Support for multiple front-ends
 - Reconfigurable FPGA-based design
 - SRAM FPGA co-processor

- First instantiation
 - SGR-ReSI for remote sensing
 - First flight is on TechDemoSat-1
 - Launch 2012/13
 - Primary goals –
 - Replacement for SGR-10
 - Ocean roughness sensing through reflectometry
 - May also demonstrate the ability to provide earthquake warning measurements .



SSTL-50 Platform



PAYLOAD MASS

IR Optics – 6 x 2kg = 12 kg

GNSS receivers = 1 kg

Total = 13 kg

PAYLOAD POWER

IR Optics – 6 x 2 W = 12 W

GNSS receivers = 4 W

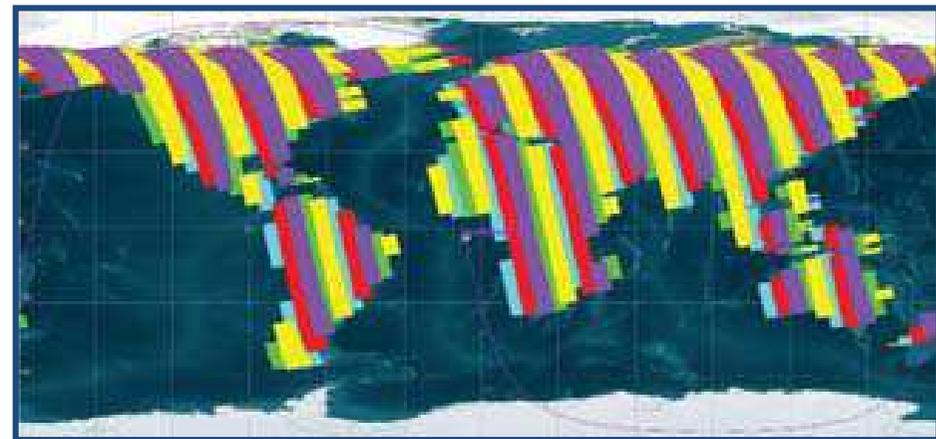
Total
= 16 W

| Mission and System | |
|--------------------------------|-----------------------------|
| Reference Orbit | 686 km, SSO, 10:30 am LTAN |
| Design Lifetime | < 5 years |
| Redundancy Philosophy | Asymmetric / Graceful |
| Typical Payload Accommodation | |
| Mass | ~ 20 kg |
| External / Internal volume | 300x 300x 350 mm / Flexible |
| Orbit Average Power | > 20 W |
| Data Storage | 128 GByte |
| Data Downlink Band / Rate | X-Band / 40 - 105 Mbps |
| F1 Platform Specification | |
| Pointing Knowledge | <0.05 ° (99.7% confidence) |
| Max. Slew Rate/ Rate Stability | 3 °/s / 0.005 °/s |
| Orbit Knowledge | 50 m (99.7% confidence) |
| De-orbit Capability | Passive - Sail |

Platform design includes magnetometers which may also have a role to play

System Concept

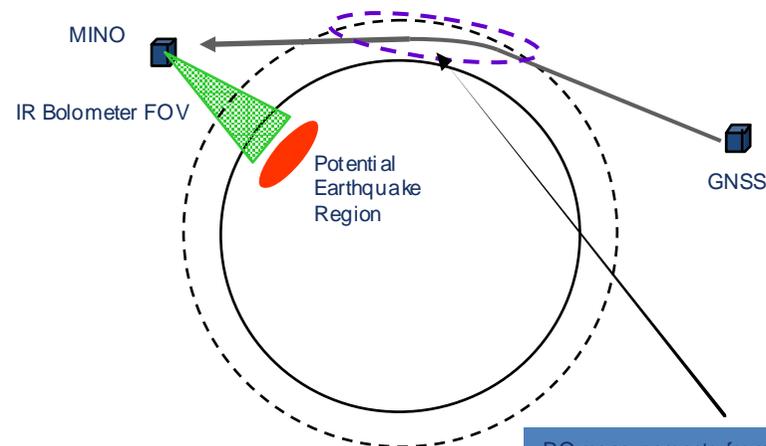
- 6 satellites - 5 operational missions and one on-orbit spare in one orbit plane
- Launch on a single vehicle into a single low Earth orbit at 60 degrees inclination
 - An orbit altitude providing a ground-trace repeat may be favoured to allow automated data processing
- At least two IR passes per day over all land areas, one ascending and one descending



Illustrative daily IR coverage from constellation of 5 satellites in a 700 km altitude orbit

System Concept

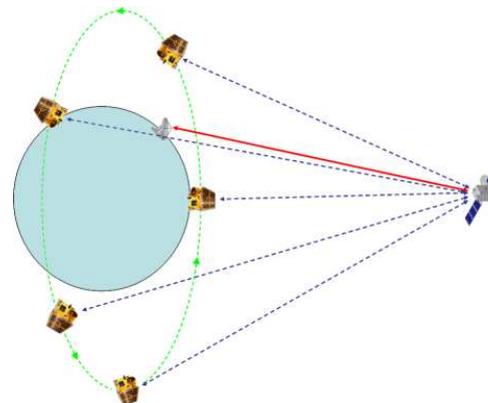
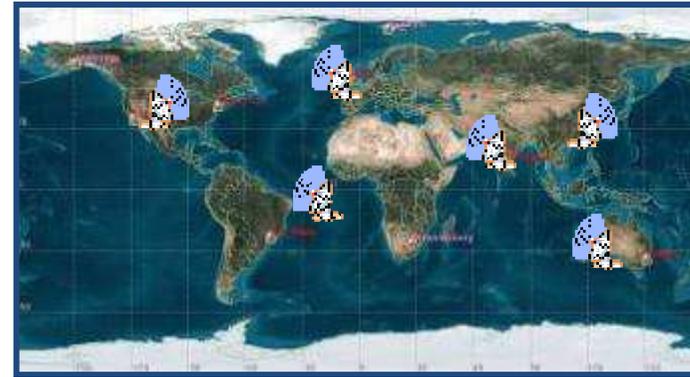
- Ideally for correlation, we would want to simultaneously measure multiple parameters over the same ground area (i.e. measure temperature changes and ionospheric perturbations over the same area at the same time)
- However, the required geometry for GNSS occultation measurements means that it will not be possible to have collocated, contemporaneous measurements from a single spacecraft
 - Occultation measurements (for e.g. Total Electron Count measurements) observe along the line of sight through the Earth limb to the GPS satellites
 - The IR coverage would occur at the sub-satellite point
- Need to build up coverage over the target area via time-separated measurements from multiple satellites



RO measurements from the MINO satellite observe the ionosphere along the line of sight to the GPS satellite, which is not coincident to the area observed by the IR payload

Communications Architecture

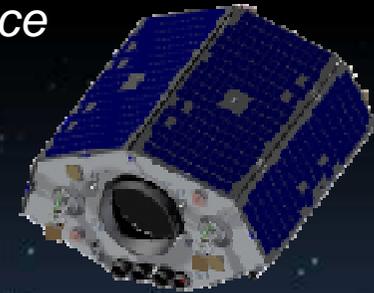
- A first-generation system would probably need to downlink data to a network of 4-6 ground stations in order to provide timely warning a few days in advance
- With improved on-board processing and inter-satellite link capabilities, a second generation system could provide an even more responsive service





Conclusions & Outstanding Questions

- A constellation of 6 satellites could make a significant contribution to earthquake forecasting, up to a week in advance of the event itself
 - IR detectors could pick up thermal anomalies
 - GNSS occultation could provide data for correlation
- A trial constellation could address outstanding questions
 - Do the observed signatures occur in association with all types of earthquakes?
 - Does the magnitude/intensity of the observed signatures correlate with the magnitude of the subsequent earthquake?
 - Do the observed signatures ever occur in the absence of an earthquake event?



Thank you for the inspiration,
Mino