The e-CUBES Space demonstrator: A flying 5 node WSN demonstrating self-localization and dynamic multi-hop networking

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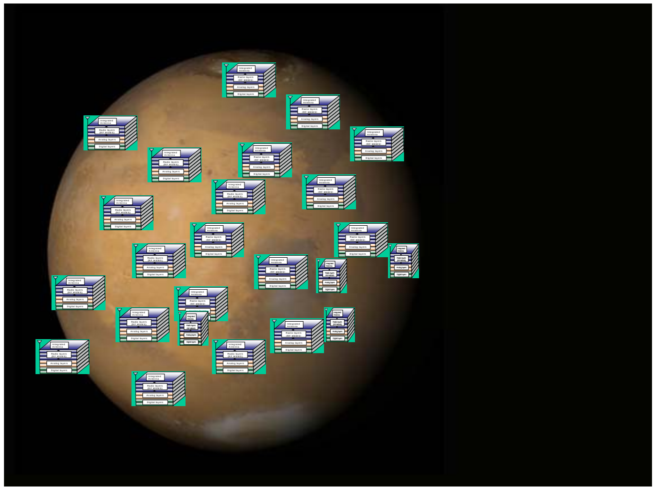
Outline

1. Why Wireless Sensor Networks for space and planetary exploration? (p. 3)
2. Some proposed scenarios using WSNs for space exploration (p. 7)
3. The e-CUBES “space” demonstrator (p. 12)



WSN in space?

In the short term, WSN are only planned in space on spacecraft (max radio range of order 5 m) as a way of reducing cabling mass and complexity

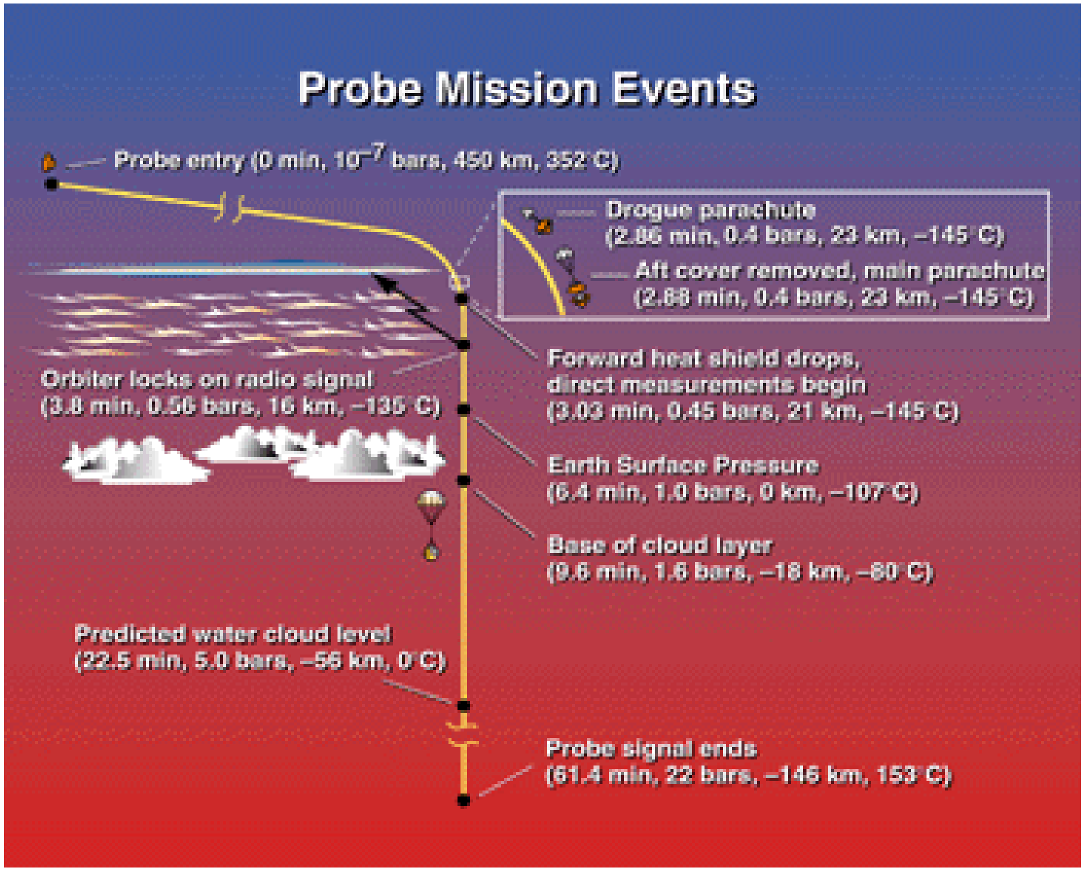
WSN enable a different way of collecting data on planets (surface and atmosphere), asteroids

- In this presentation, possible uses of WSNs for exploring space are presented, where WSN replace or complement larger (more expensive) spacecraft

In all scenarios addressed here, it is assumed that the same orbiter that delivered the hundreds or thousands of nodes to the planet also acts as a relay to forward the acquired data back to Earth.

An example of a single probe mission (no WSN)

Galileo mission, **atmospheric probe** on Jupiter:



First probe to sample the atmosphere of a gas planet

Data collected:

Local weather:

- wind speed
- temperature
- pressure
- chemical composition
- sunlight energy
- lightning

Radio:

- 1.4 GHz
- Crossed dipole pair antenna

Total energy stored:

- 700Wh

Single probe mission vs. WSN based missions

Scientific & technical considerations

	Single instrument	AD-HOC WSN
Complex sensing involving long-range measurements **(spectrometry, Lidar, optical, imaging)**	•Largely reported on past missions. •Can provide a large amount of data with a single probe.	•Difficult due to: • miniaturization (physical limit on sensor size) • fabrication cost • amount of data provided
Localized simple measurements **(temperature, pressure, gas sensing, humidity, light intensity)**	•Reported on past missions. •The data is only provided for a single location on a planet or asteroid.	• Never tested with large amount of probes (N>2) • Could enable mapping over a large area or volume and for a long period of time. • Robust due to the AD-HOC network structure

Single probe mission vs. WSN based missions

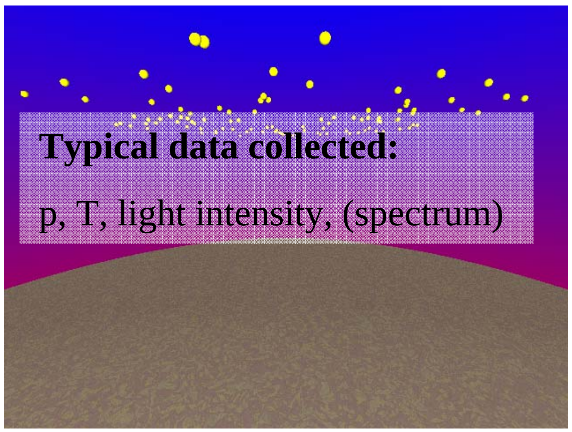
Economic considerations

	Single instrument	AD-HOC WSN
Complex sensing involving long-range measurements **(spectrometry, Lidar, optical, imaging)**	•High reliability of each element required •Each element fully space qualified •Never off the shelf elements. •Very costly	•High <u>global</u> reliability of WSN required •Off the shelf WSN do not match space requirements •Few off the shelf sensors are suitable •Costly
Localized simple measurements **(temperature, pressure, gas sensing, humidity, light intensity)**	•High reliability of each element required. •Each element fully space qualified. •Never off the shelf elements. •Very costly.	• High <u>global</u> reliability of WSN required. • Off the shelf WSN do not match space requirements • Some off the shelf sensors exist • Could become a less costly exploration method

Example WSN scenarios based on moving nodes

Scenario 1.1:

Cloud of sensing nodes (5-100) falling in the atmosphere of a planet (Venus). The relay falls along with the nodes.

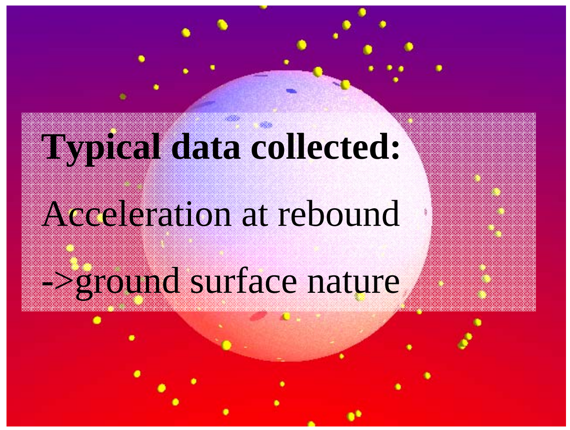


Technical "+": Low stored energy required, short lifetime required

Technical "-": Evolving data routes
Scientific interest: moderate

Scenario 1.2:

Data collection with network of **sensor nodes rebounding** on the ground of a low gravity solar system objects.



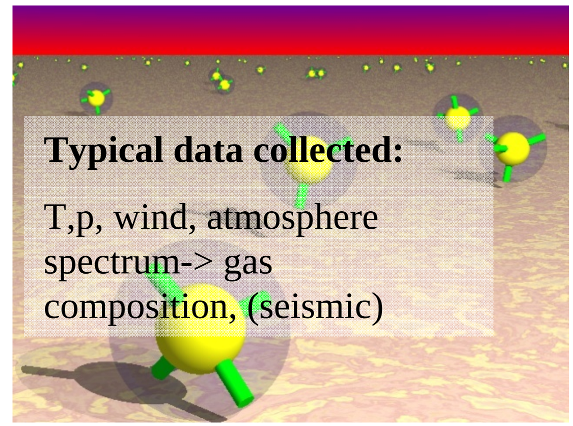
Technical "+": communication without obstacle

Technical "-": Quickly evolving data routes

Interest: TBD

Scenario 1.3:

Network of sensor nodes using **energy scavenging** and **individual node propulsion.**

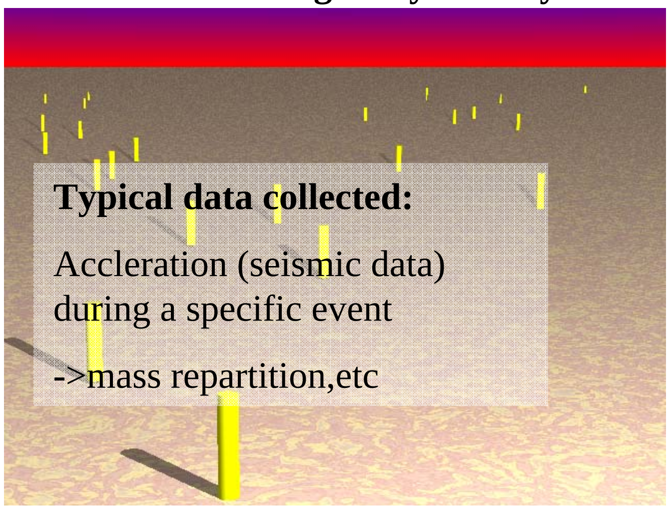


Technical "+": simplified distribution, slow motion and network update
Technical "-": obstacles to wave propagation, long lifetime
Scientific interest: long term exploration, great interest

Example WSN scenarios based on fixed nodes

Scenario 2.1:

Data collection with network of sensor nodes **attached to the surface of a low gravity solar system objects.**



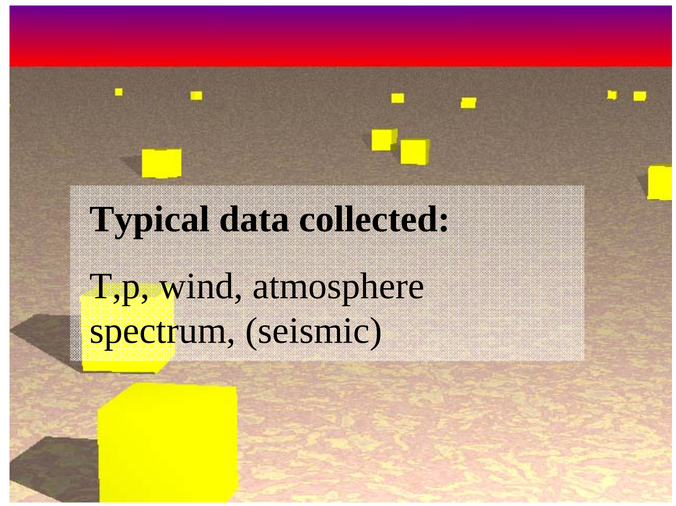
Technical "+": No communication needed during measurement

Technical "-": large acceleration at impact

Scientific interest: could be of great interest

Scenario 2.2:

Data collection with network of sensor nodes **laying on the ground of planets or moons.**



Technical "+": Slow data rate

Technical "-": Wave propagation depends on the roughness of the planet surface

Scientific interest: significant interest to measure in a distributed fashion with simple sensors.

Node distribution methods

	Advantages	Drawbacks	Typical missions
Initial momentum	• Simplicity • Small node size • Could allow large distance distribution	• Could involve high accelerations • Not accurate	• Atmospheric & ground measurements
Dropped from a spacecraft	• Simplicity • Small node size • Could allow large distance distribution	• Could involve high accelerations • Not accurate	• Atmospheric & ground measurements
Distributed with a rover	• Accurate distribution • No need for node self-localization • Small node size	• Time consuming • Limited range	• Ground measurements
Individual propulsion	• Low accelerations • Could enable an accurate distribution	• Very complex • Large node size	• Atmospheric & ground measurements

Node localization techniques

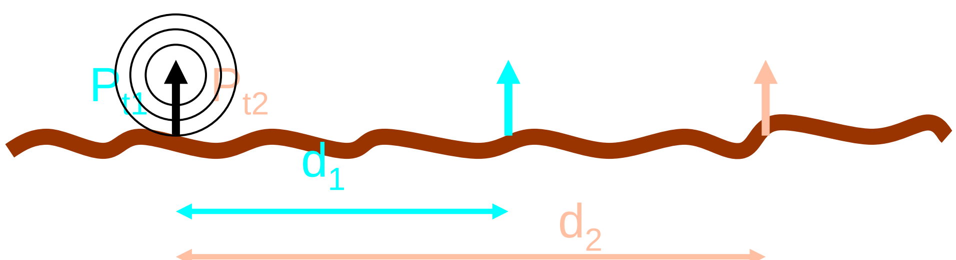
	Advantages	Drawbacks
Electromagnetic wave propagation delay	• Can be very accurate • Continuous self-localization	• Ambiguity due to multiple reflections • Could require UWB which might not be ideal for long distance communication
Signal strength	• Simplicity • Continuous self-localization	• Not accurate
GPS type	• Accurate • Well established • Continuous self-localization	• Large infrastructure required, numerous satellites orbiting
Optical	• Can be accurate	• Need to rely on central data processing (at the base station) • New development • Continuous self-localization difficult

Example specifications of a node network fixed on the ground, scenarios

Estimated typical node network on the ground of a solar system object. Specifications will be different for different missions.

Node # & distance	Localization	Typical sensors	Data rate of each node	Sensor power	Power @ 1node for the transceiver	Total power/ node	Total energy active 1 hour/day 1 year
100 nodes 1 km	Required	T, p	4 byte/h	20 μW	1mW	1mW	365mWh

Power/transmission distance relation:



$$P_{t2} = P_{t1}\left(\frac{d_2}{d_1}\right)^n$$

Depending on the transmission media:

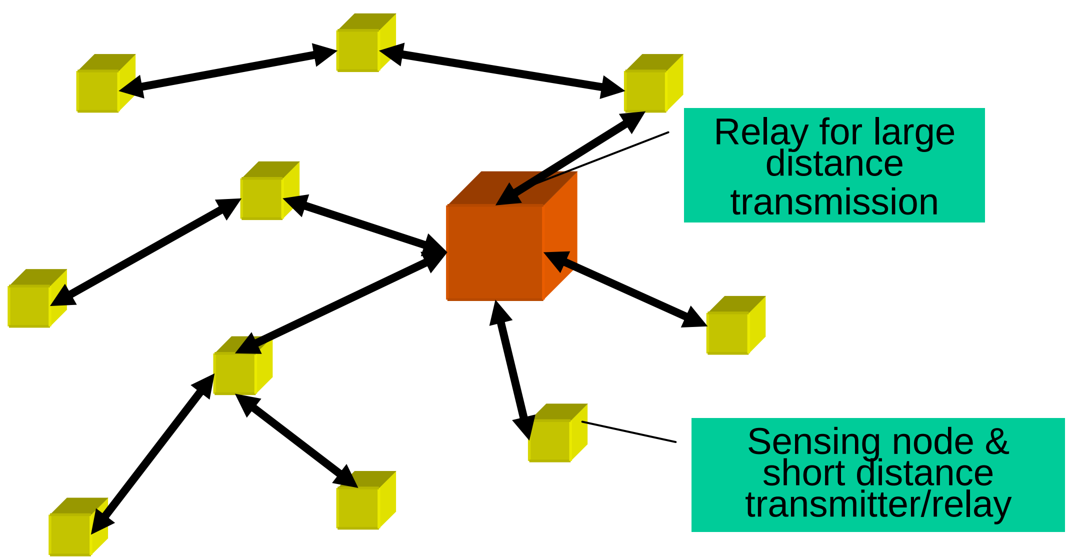
- 3<n<5 antenna on the ground with reflections
- n=2 in free space

e-CUBES Demo for Space Applications

As seen above there are many possible scenarios for using WSN for distributed exploration of planets, their atmospheres, asteroids...

The e-CUBES space demonstrator (on earth) will perform distributed measurements in the atmosphere, **demonstrating key general features**:

- ad-hoc mesh network with rapid dynamic networking
- self-localization with coordinates transmission through the network
- long-range communication (5 km)



Are Commercial WSN platforms suitable for space exploration?

Characteristics

- AD-HOC functionality
- relatively low power consumption
- robust transmissions
- can be interfaced with simple analog or digital sensors

Limitations

- not space qualified
- do not provide localization
- have usually a short transmission range < 200 m in outdoor

Can be suitable for concept evaluation on earth

WSN for space exploration need additional development in order to meet mission requirements

e-CUBES "Space" Demonstrator

5 nodes, each on one paraglider. One additional fixed node on the ground serves as gateway, while the others fly around for several hours, covering up to 10x30 km^2.

Demonstrate:

- **<u>Dynamic</u> <u>self-organized</u> Mesh network, with links up to 5 km, data point transmitted every 1-20s.**
- **<u>Localization</u> (via GPS) & coordinates transmission through the WSN**

General considerations on algorithm & software (differences between space and terrestrial WSNs)

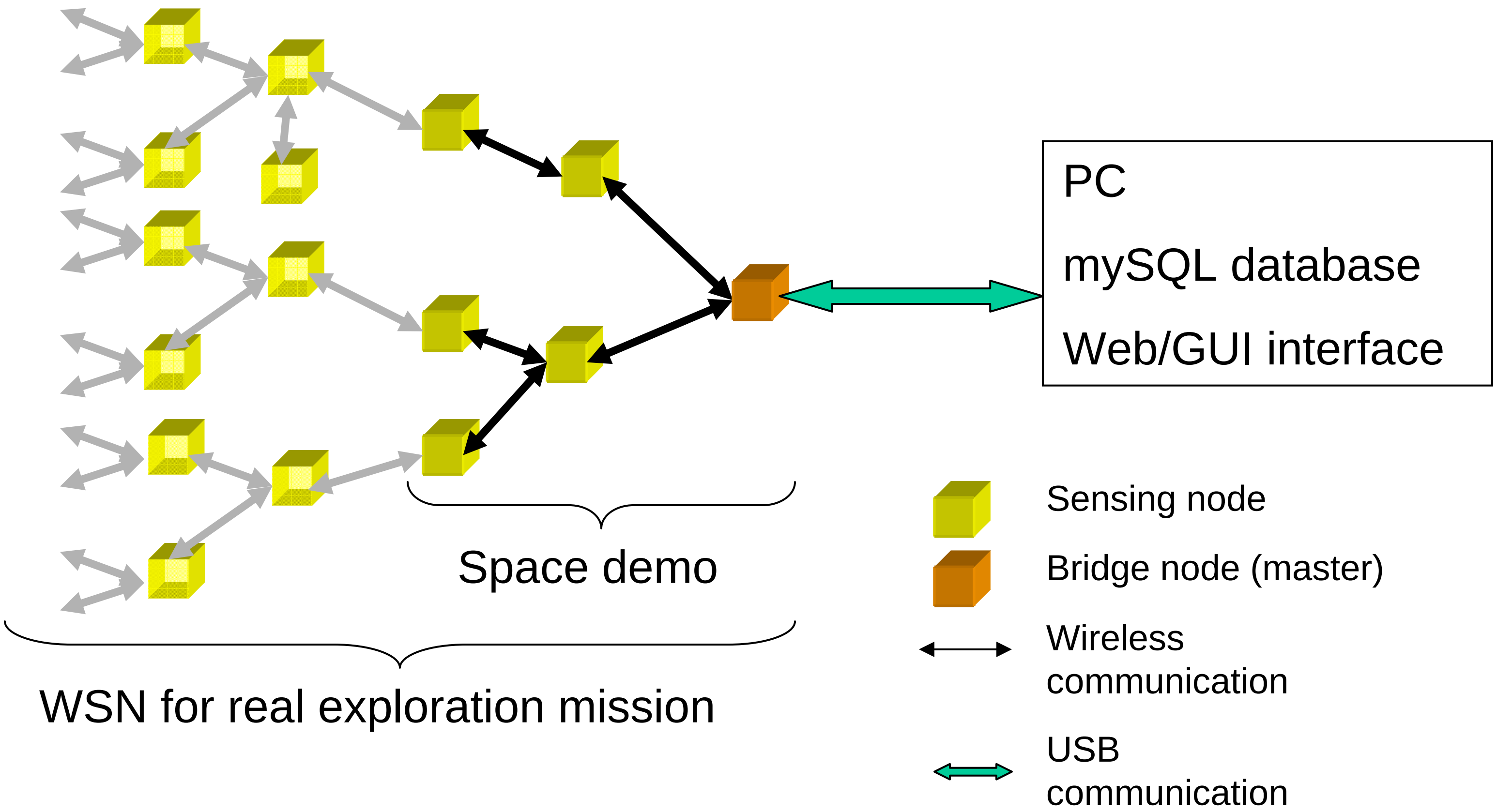
Specific requirements of WSN for space exploration:

- Mobility of the nodes
- Localization of the nodes required (need to know accurately the location of the measurements)
- High sampling rate for dynamic scenarios
- Heterogeneous network is acceptable (sensing and relay nodes)
- Size, weight, calculation and power limitations for the sensing nodes, but not for the master node located in the space craft
- Highly fault tolerant

Centralized vs. decentralized approach:

- Centralized approach takes advantage of the larger resources (RF transmit power, antenna size, computation power…) available to the master node.
- Decentralized is most useful when the access point to the network is changing and direct communication from the master node toward sensing node is not feasible or not garanteed. Also best for networks having very large numbers of nodes (>1000)

e-CUBES Space demo WSN organization and topology



We choose, due to the high sampling rate, a WSN organization where nodes spontaneously sample and transmit data toward the master node.

Example of specs (highly mission dependent)

	Demo in Earth atmosphere	Mission in Venus Atmosphere
# of nodes	5-10	50-200
Relay/Gateway	On ground	Falling with nodes (numerous relays possible)
Localization	GPS	LIDAR or RF TOF
Size	200 cm^3 (without GPS)	3 cm^3
RF Frequency	868 MHz	868 MHz or other
Power supply	Lithium battery (~2Ah, 3.6V)	Battery
RF power	Max allowed by regulation	Unregulated
Node speed	< 10 m/s	< 100 m/s
RF range between cubes	5 km	25 km (from Relay to Orbiter> 1000 km)
Minimum data rate per node	64 bit/s	640 bit/s
Operating time	1 hour	4 hours
Radiation tolerant	No	Yes
Environment	Benign	Corrosive

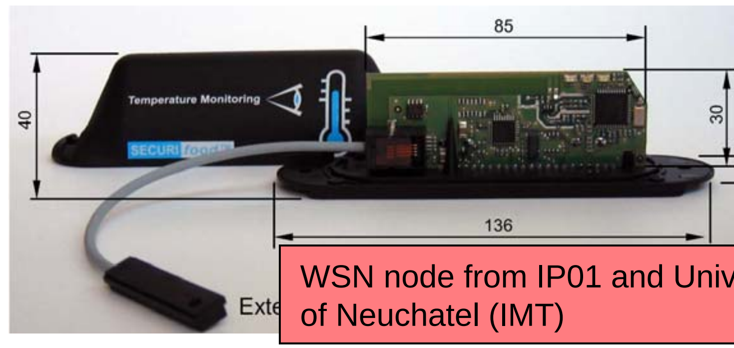
“Space demo” hardware

- For demonstration, cannot wait for integrated e-CUBES radio, nor can we expect an e-CUBES radio to meet the range (>5km). So we modified node hardware from partners in a Swiss project.

- Hardware and mesh networking software is based on product and research from IP01 (Neuchatel, Switzerland) and IMT, University of Neuchâtel.

- Main modification to existing hardware is integration of GPS for each node and modification of antenna

- Software modified to allow true multi-hop networking



WSN node from IP01 and University of Neuchatel (IMT)

+

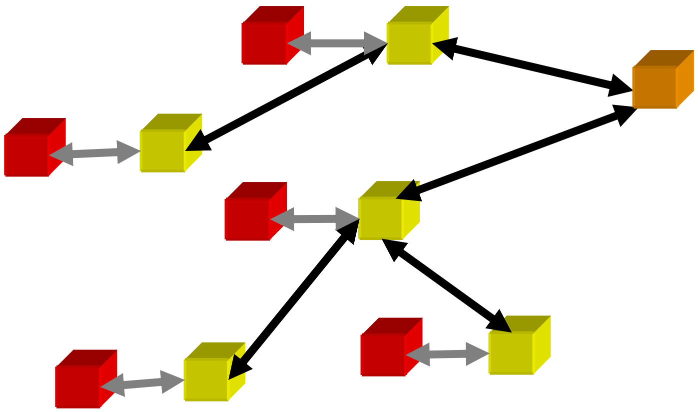
Characteristics:

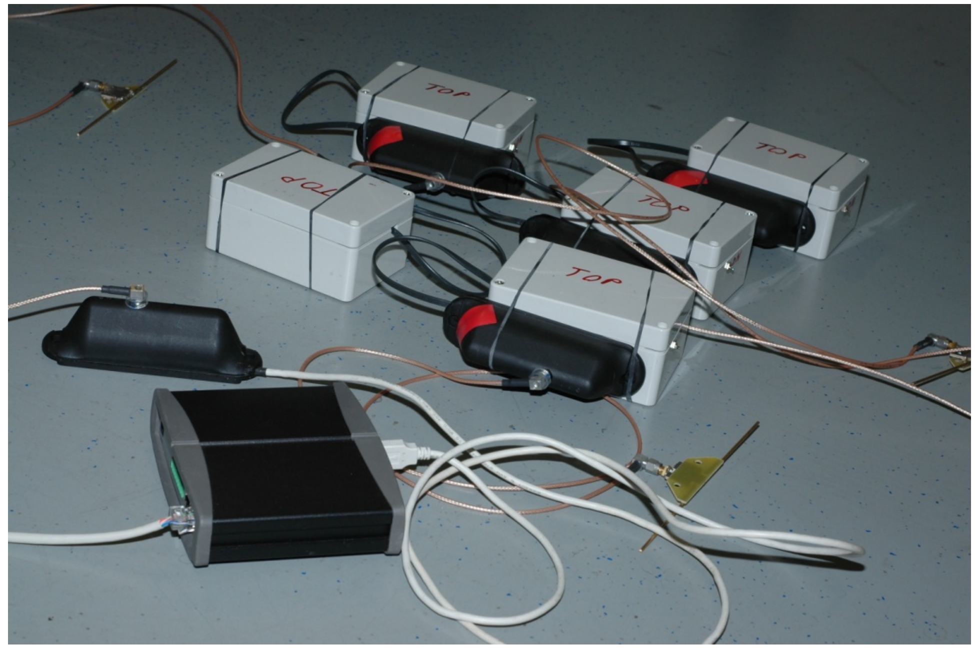
Output amplifier power = 13.5 dBm, dipole antenna gain = 2dBi

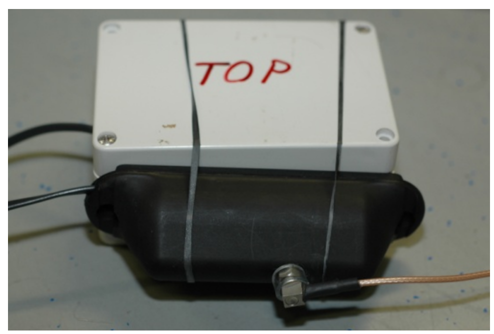
Consumption: sleep = 2µA, active = 300 µA

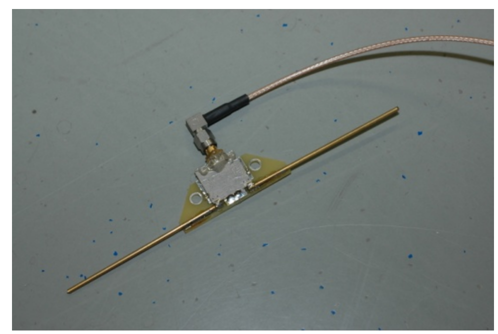
Sensitivity = -112 dBm

eCUBES “Space demo” hardware









Master node

Sensing node

GPS

Wireless communication

I2C communication

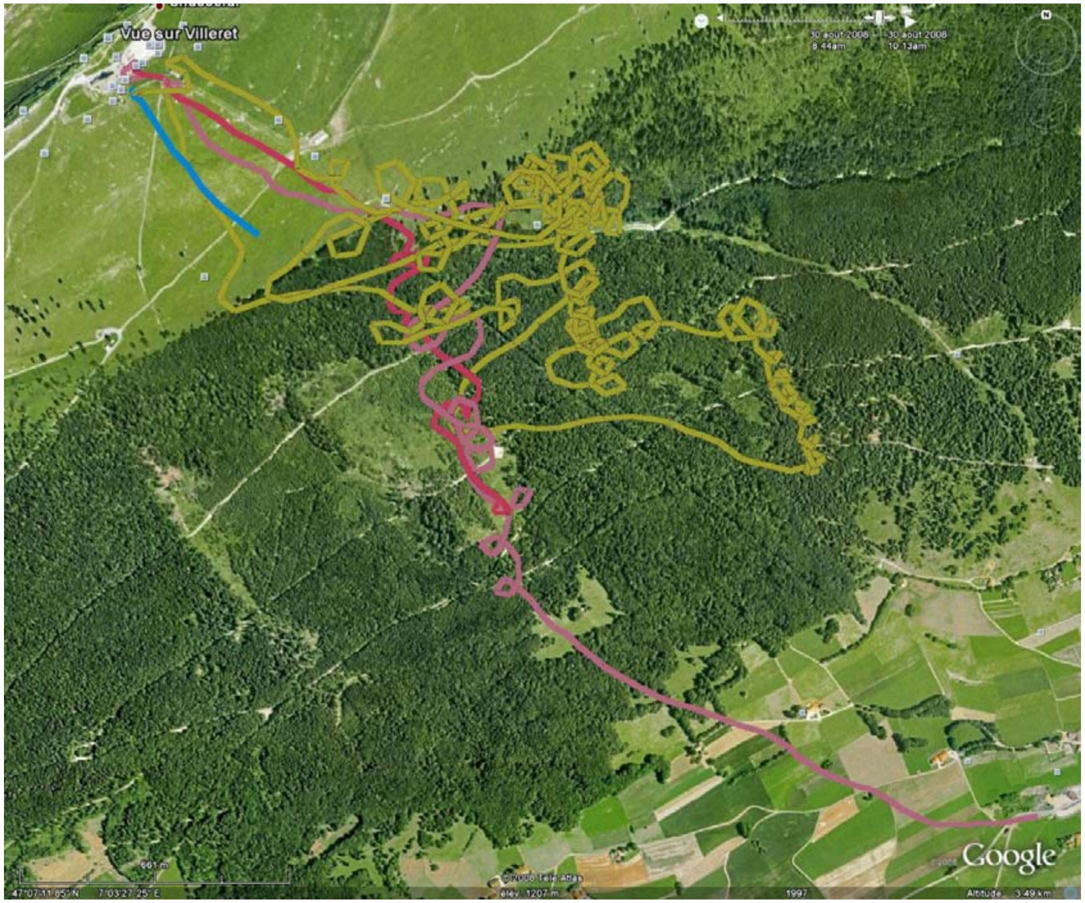
Initial Test results: Real time localisation

The database on the master node is automatically filled during the test, as the paragliders fly with the nodes.

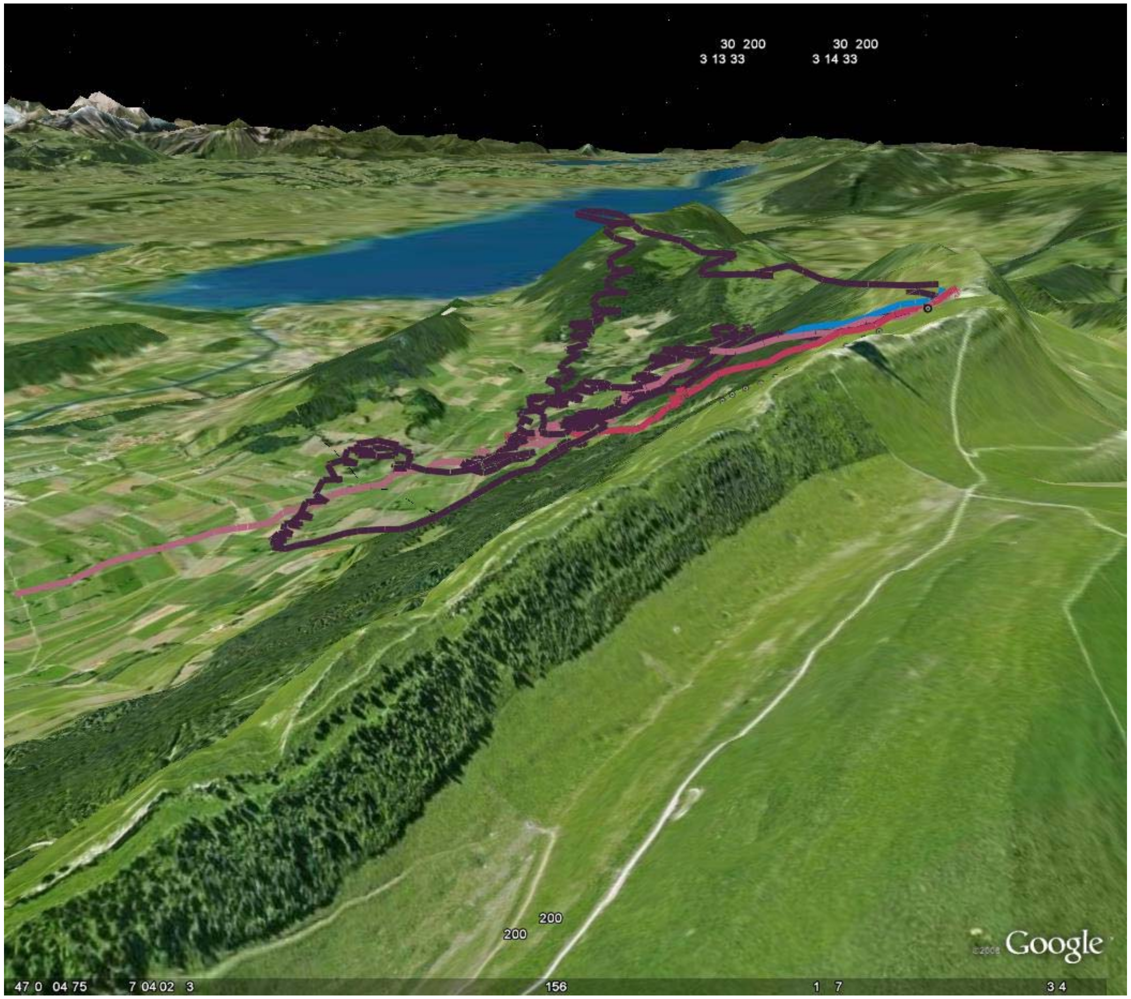
A PHP program extracts coordinates from a database and exports them into a Google Earth file (.kml) after a sorting process. The visualization can be done during the deployment enabling the tracking of the nodes. Post visualization allows to analyze communication losses while providing a 3D view.

Localization data obtained by GPS was sent every 5 seconds to the ground. **Self-Localization was thus demonstrated.**

The maximum distance of communication is over 6 km in direct line of sight.



The goal is not to simply to get GPS data from paragliders, as this could be done by GPS logging, or GPS + mobile phone. The Goal is to show long-range multi-hop data transmission, with GPS as an example of self-localization.



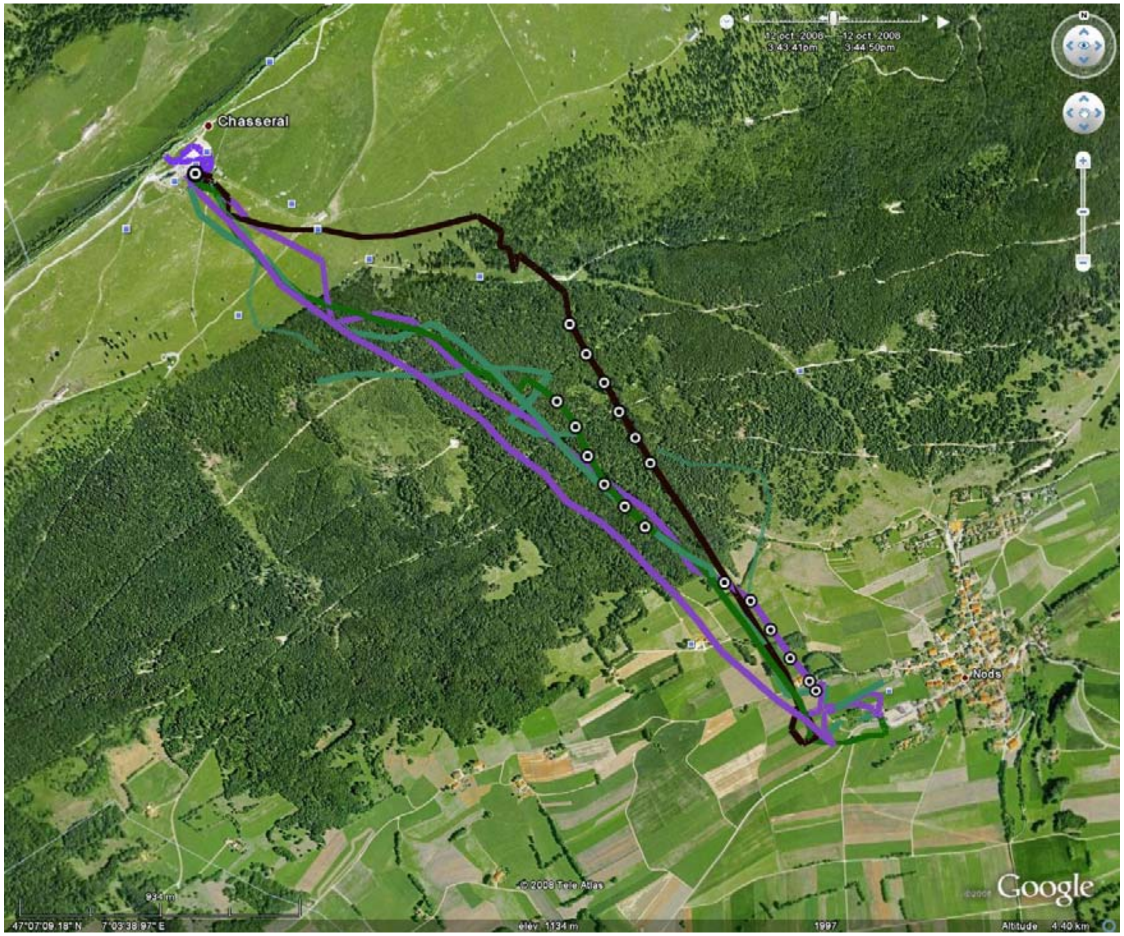
See related movie of paragliders carrying the nodes for details on node placement in backpack and testing environment.

Test results: Mesh functionality of a dynamic WSN (1)

We tested a reconfigurable mesh network with up to 5 nodes transmitting in real time sensed data (location) trough the network using the multi-hop functionality.

The sampling time was increased from 5 to 12 s to guaranty no data loss due to network congestion even when the nodes are organized in a chain having 5 communication hops.

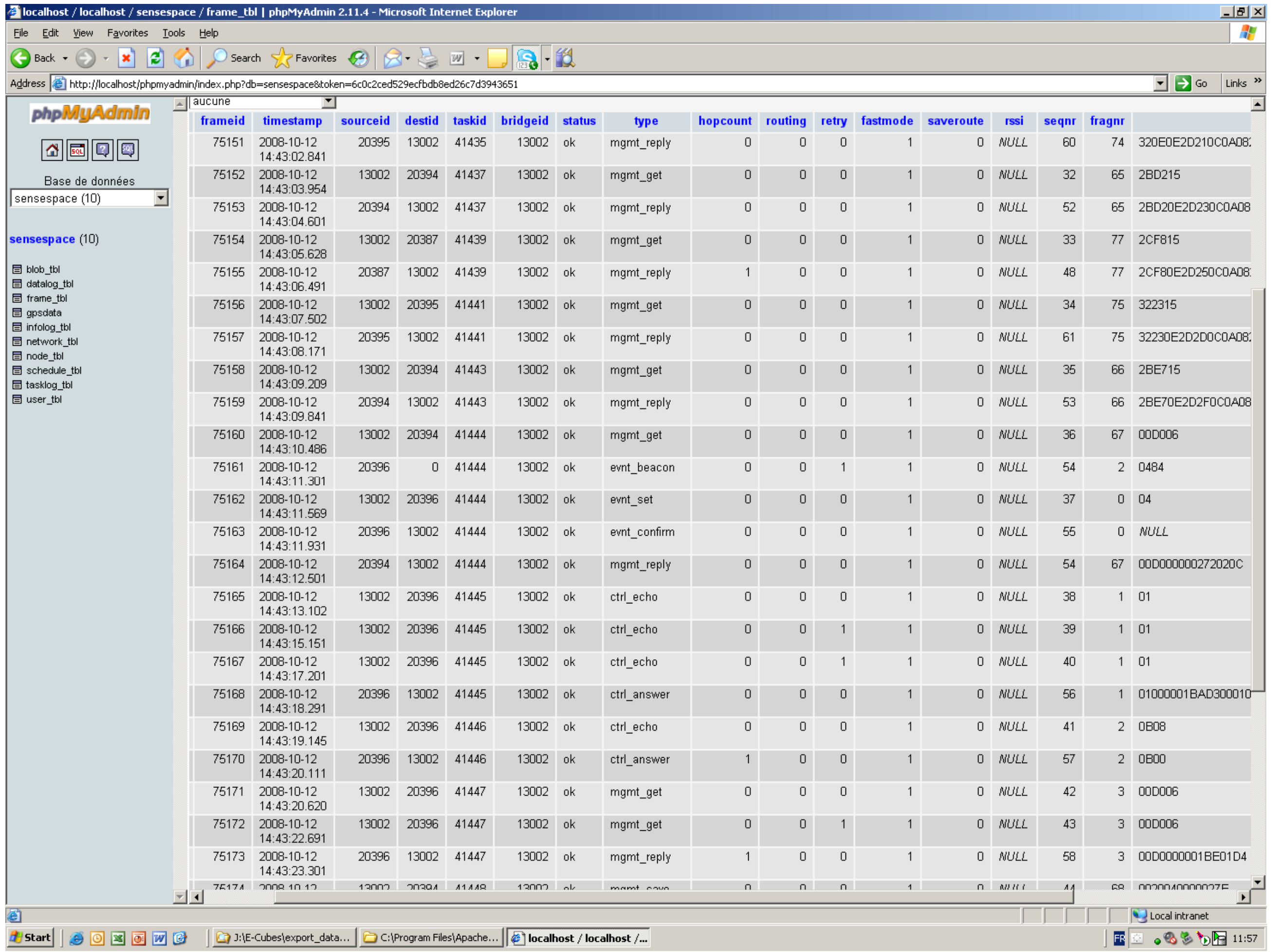
The nodes were flying at a ground speed of about 10 m/s.



Test results: Mesh functionality of a dynamic WSN (2)

During the flight we observed situations where the data followed up to three hops to reach the base station. This occurred for different source nodes.

This demonstrated the multi-hop mesh network behavior



frameid	timestamp	sourceid	destid	taskid	bridgeid	status	type	hopcount	routing	retry	fastmode	saveroute	rssi	seqnr	fragnr	
75151	2008-10-12 14:43:02.841	20395	13002	41435	13002	ok	mgmt_reply	0	0	0	1	0	NULL	60	74	320E0E2D210C0A08
75152	2008-10-12 14:43:03.954	13002	20394	41437	13002	ok	mgmt_get	0	0	0	1	0	NULL	32	65	2BD215
75153	2008-10-12 14:43:04.601	20394	13002	41437	13002	ok	mgmt_reply	0	0	0	1	0	NULL	52	65	2BD20E2D230C0A08
75154	2008-10-12 14:43:05.628	13002	20387	41439	13002	ok	mgmt_get	0	0	0	1	0	NULL	33	77	2CF815
75155	2008-10-12 14:43:06.491	20387	13002	41439	13002	ok	mgmt_reply	1	0	0	1	0	NULL	48	77	2CF80E2D250C0A08
75156	2008-10-12 14:43:07.502	13002	20395	41441	13002	ok	mgmt_get	0	0	0	1	0	NULL	34	75	322315
75157	2008-10-12 14:43:08.171	20395	13002	41441	13002	ok	mgmt_reply	0	0	0	1	0	NULL	61	75	32230E2D2D0C0A08
75158	2008-10-12 14:43:09.209	13002	20394	41443	13002	ok	mgmt_get	0	0	0	1	0	NULL	35	66	2BE715
75159	2008-10-12 14:43:09.841	20394	13002	41443	13002	ok	mgmt_reply	0	0	0	1	0	NULL	53	66	2BE70E2D2F0C0A08
75160	2008-10-12 14:43:10.486	13002	20394	41444	13002	ok	mgmt_get	0	0	0	1	0	NULL	36	67	00D006
75161	2008-10-12 14:43:11.301	20396	0	41444	13002	ok	evnt_beacon	0	0	1	1	0	NULL	54	2	0484
75162	2008-10-12 14:43:11.569	13002	20396	41444	13002	ok	evnt_set	0	0	0	1	0	NULL	37	0	04
75163	2008-10-12 14:43:11.931	20396	13002	41444	13002	ok	evnt_confirm	0	0	0	1	0	NULL	55	0	NULL
75164	2008-10-12 14:43:12.501	20394	13002	41444	13002	ok	mgmt_reply	0	0	0	1	0	NULL	54	67	00D000000272020C
75165	2008-10-12 14:43:13.102	13002	20396	41445	13002	ok	ctrl_echo	0	0	0	1	0	NULL	38	1	01
75166	2008-10-12 14:43:15.151	13002	20396	41445	13002	ok	ctrl_echo	0	0	1	1	0	NULL	39	1	01
75167	2008-10-12 14:43:17.201	13002	20396	41445	13002	ok	ctrl_echo	0	0	1	1	0	NULL	40	1	01
75168	2008-10-12 14:43:18.291	20396	13002	41445	13002	ok	ctrl_answer	0	0	0	1	0	NULL	56	1	01000001BAD300010
75169	2008-10-12 14:43:19.145	13002	20396	41446	13002	ok	ctrl_echo	0	0	0	1	0	NULL	41	2	0B08
75170	2008-10-12 14:43:20.111	20396	13002	41446	13002	ok	ctrl_answer	1	0	0	1	0	NULL	57	2	0B00
75171	2008-10-12 14:43:20.620	13002	20396	41447	13002	ok	mgmt_get	0	0	0	1	0	NULL	42	3	00D006
75172	2008-10-12 14:43:22.691	13002	20396	41447	13002	ok	mgmt_get	0	0	1	1	0	NULL	43	3	00D006
75173	2008-10-12 14:43:23.301	20396	13002	41447	13002	ok	mgmt_reply	1	0	0	1	0	NULL	58	3	00D0000001BE01D4

Achievements & Observations

• A WSN with communication distance in the 5 km range, self-reconfiguration and multi-hop capability, and ability to determine node location was successfully tested during 3D displacement of up to 5 nodes at ground speed of 10 m/s

• The data (location of the nodes), was sent through the network by multiple hops to the base station allowing live tracking of their position

• We observed that the communication algorithm, amount of data transmitted and sampling rate largely influence the capacity of network to withstand large node number

• Commercial WSN products are rapidly improving and are coming close to meeting the requirements for a simple exploration mission

• A important open challenge is the node self-localization (that would obviously have to be done without GPS/Galileo in a real mission)

Optimization and Perspective

- The communication algorithm can be optimized to achieve higher sampling rate with more nodes while maintaining high robustness
- Earth testing for situations similar to a Space exploration scenario can be the basis for providing the input parameters to simulations of real exploration scenarios
- Two approaches can be followed:
    - mission oriented developments
    - generic developments that can provide adaptable WSN for a group of missions
- Mission oriented developments will allow to achieve better performances, but will be much more costly and time consuming
- Generic WSN can be an approach much less costly on the long term, taking advantage of the versatility of WSN:
    - for instance WSN with hardware and software modularity can be foreseen
- The size and weight of the nodes shall not be an issue in the future since new developments will provide tiny nodes of about 1-5 cm^3 capable of withstanding harsh environments