Environmental wireless sensor networks: a decade's journey from the lab to the field

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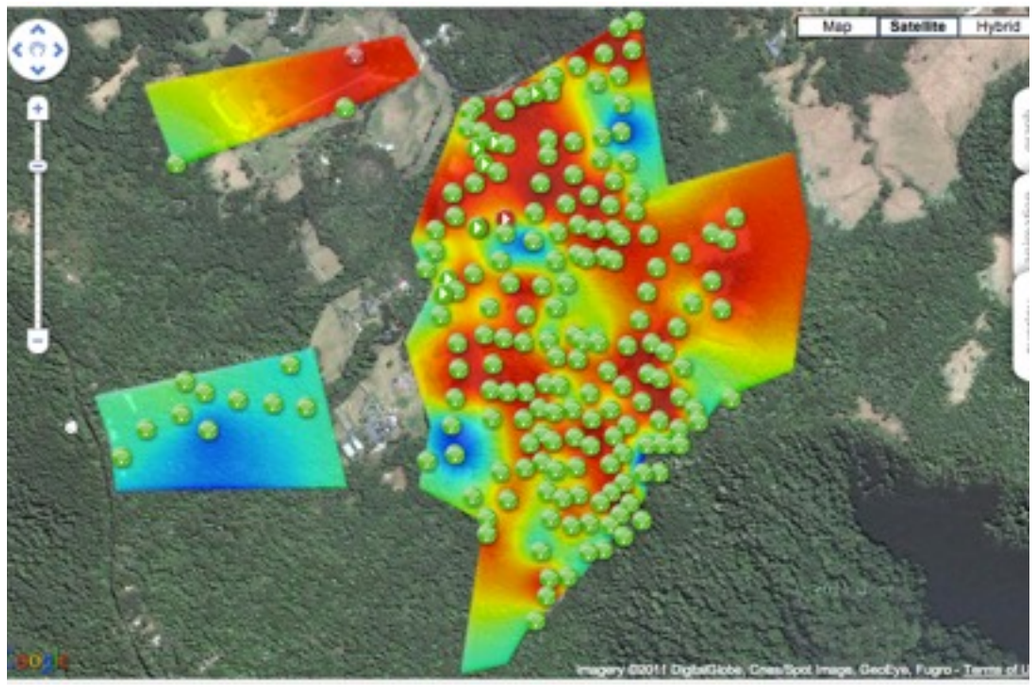
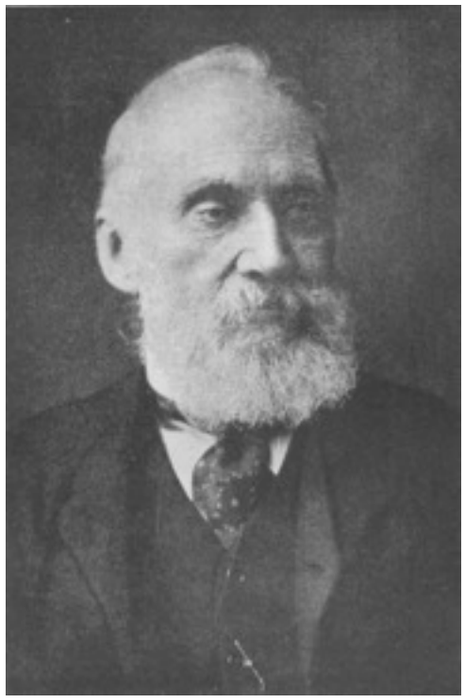
https://wiki.qut.edu.au/display/cyphy

The ten year journey



It’s all about measurement



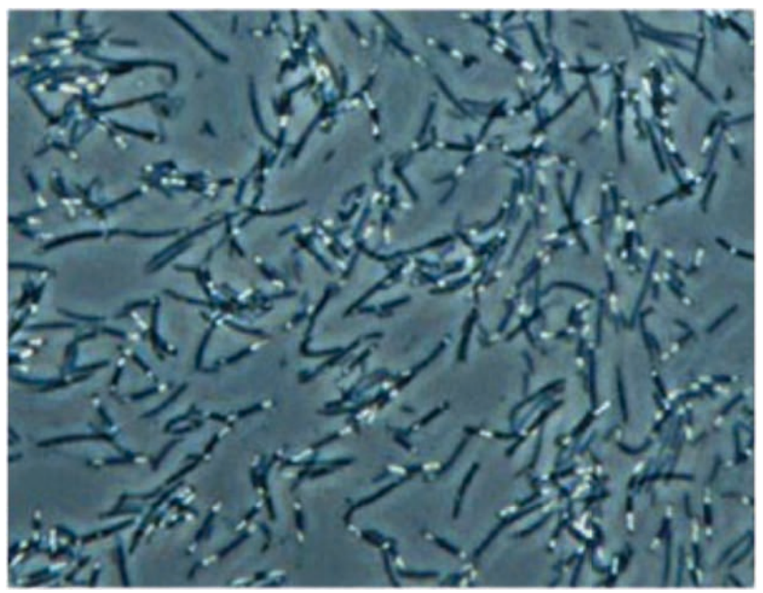
I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind.
— Lord Kelvin (William Thomson)

Facts do not cease to exist because they are ignored.
—Aldous Huxley

Measurement is the first step that leads to control and eventually to improvement. If you can't measure something, you can't understand it. If you can't understand it, you can't control it. If you can't control it, you can't improve it.
—H. James Harrington

Science is advanced by new measuring tools

"Nothing tends so much to the advancement of knowledge as the application of a new instrument."
— *Sir Humphry Davey*



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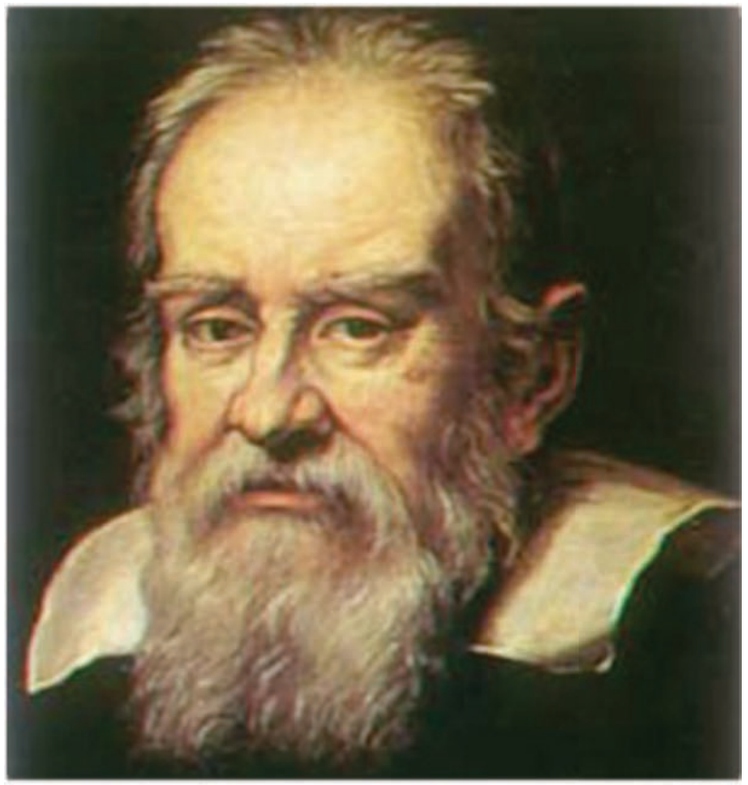

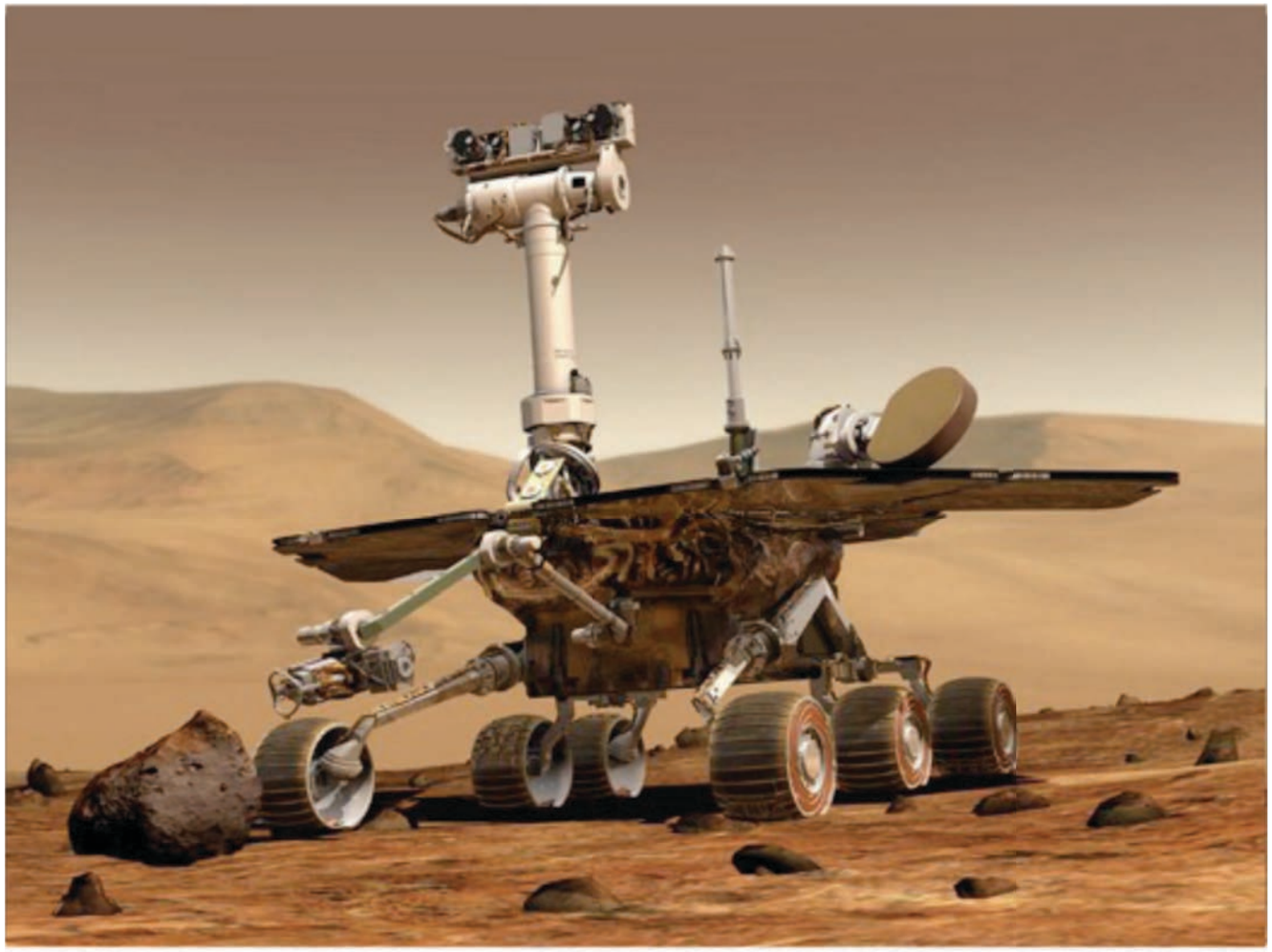

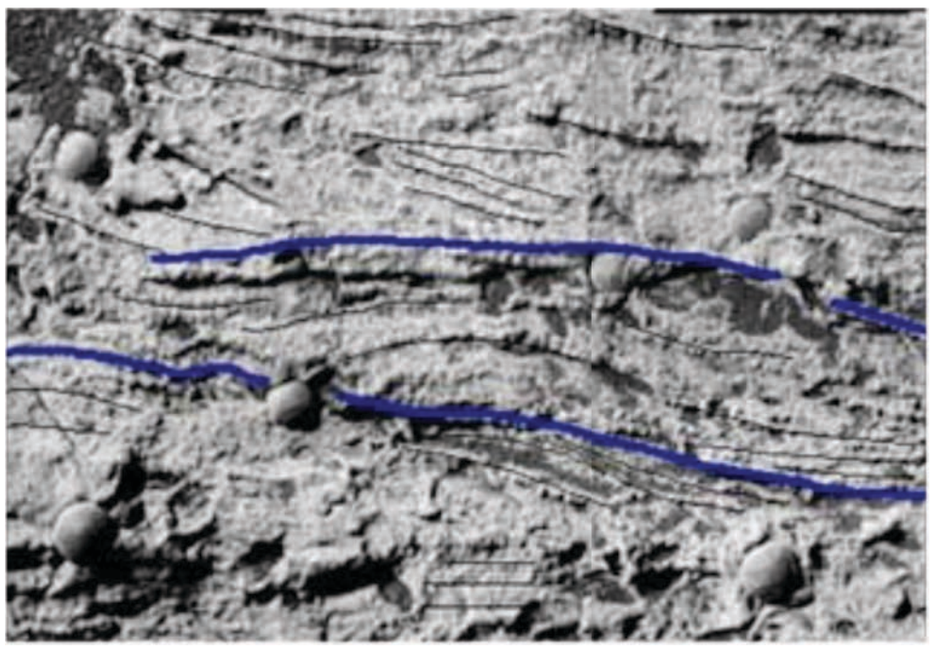

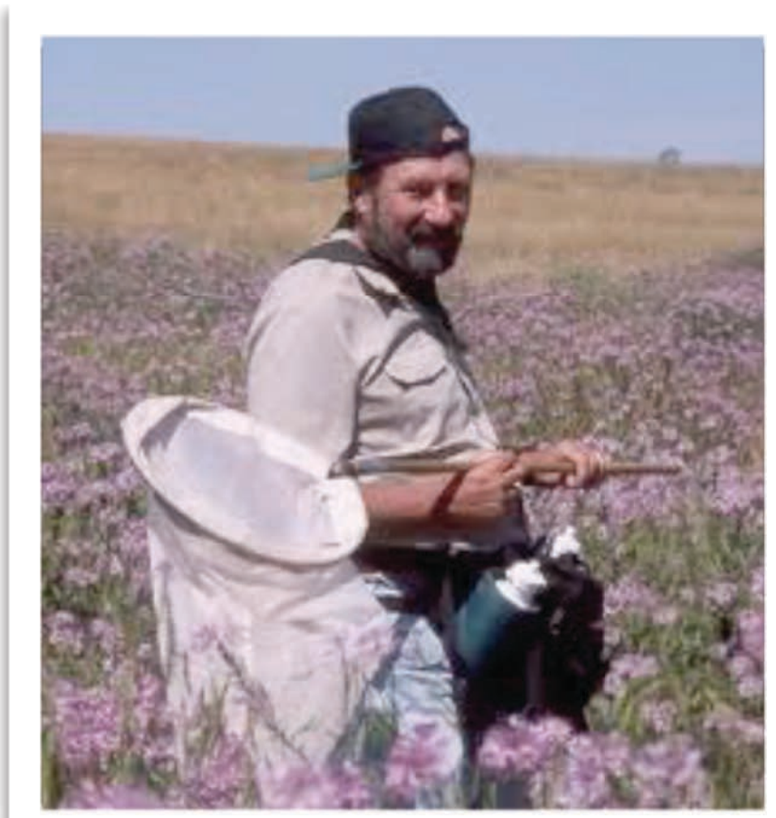

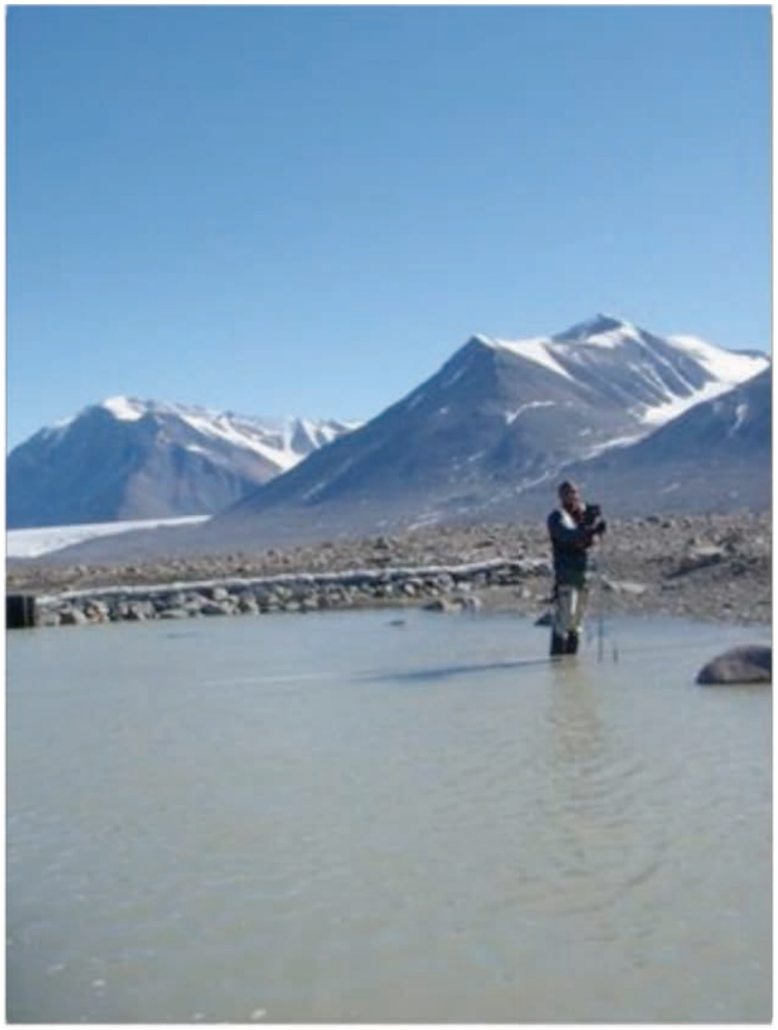

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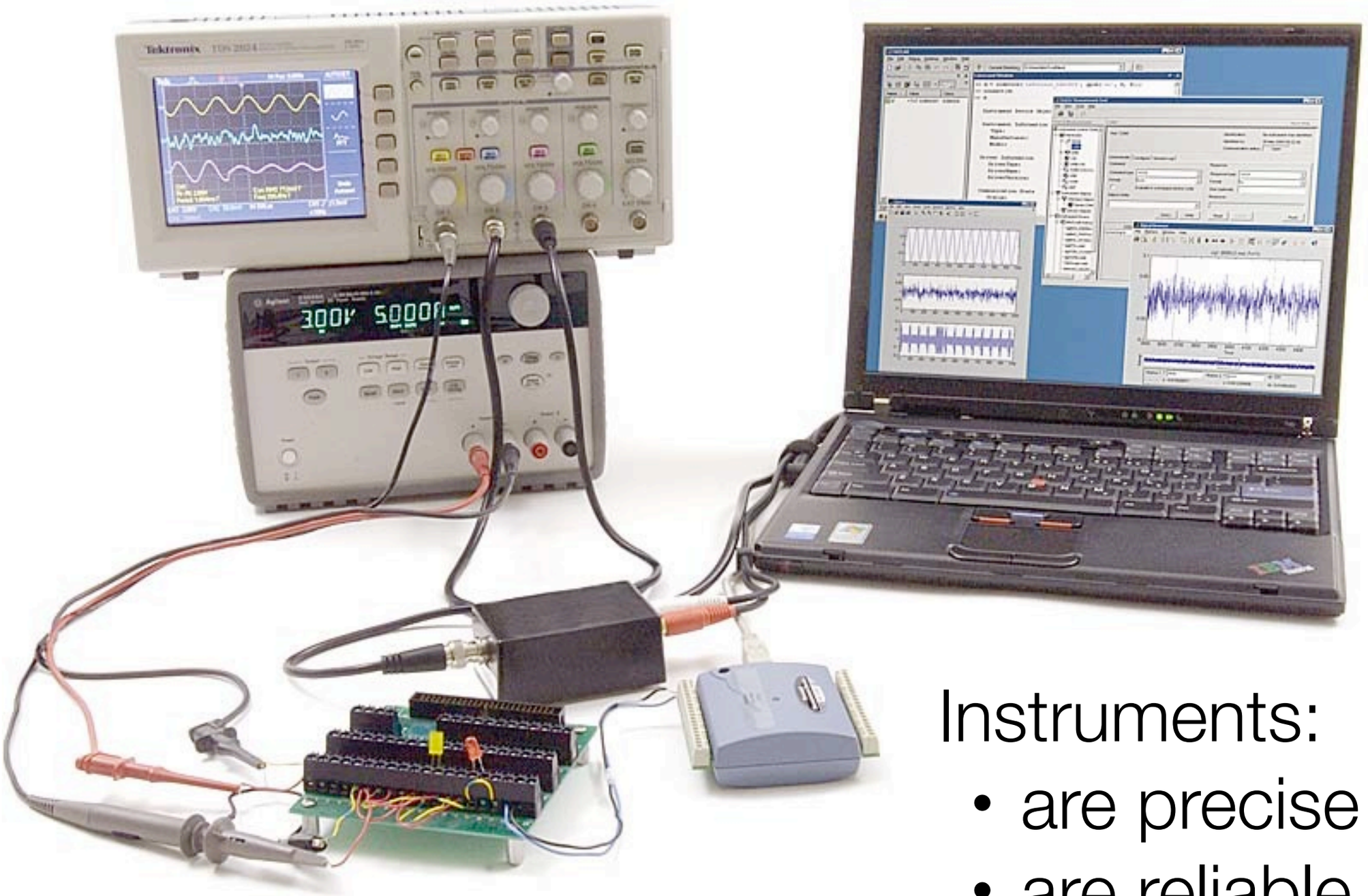
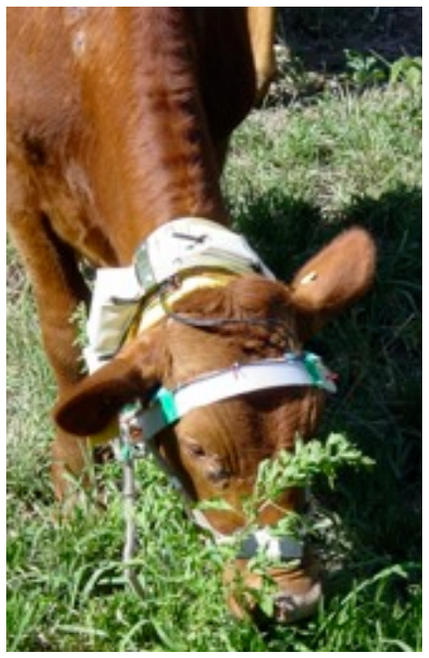


Instruments:

- are precise
- are reliable
- are easy to use
- have clear display of data



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Fleck1C	Fleck1C Fleck2	Fleck3	Fleck3	Fleck3	Fleck3

[1] P. Corke, T. Wark, R. Jurdak, W. Hu, P. Valencia, and D. Moore, "Environmental wireless sensor networks," *Proceedings of the IEEE*, vol. 98, no. 11, pp. 1903 –1917, 2010.

[2] T. Wark, P. Corke, P. Sikka, L. Klingbeil, Y. Guo, C. Crossman, P. Valencia, D. Swain, and G. Bishop-Hurley, "Transforming agriculture through pervasive wireless sensor networks," *IEEE Pervasive Computing*, vol. 6, pp. 50–57, Apr. 2007.

The CSIRO's Fleck™ Hardware

Fleck nano – fits almost everywhere

Facts: Nordic 433 or 915MHz Radio with built in MCU, Flash and accelerometer

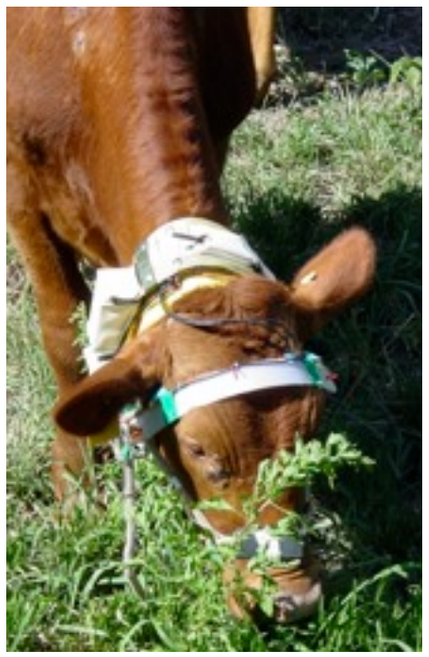
Fleck with expansion bus boards for almost any sensor

Facts: Atmel 8bit MCU, 915 or 433 MHz Nordic Radio (Range > 1000m), Solar charge Circuit, ~20 µA in sleep state

Gateway module for routing to other networks

Bridging from highly efficient WSN protocols to the internet



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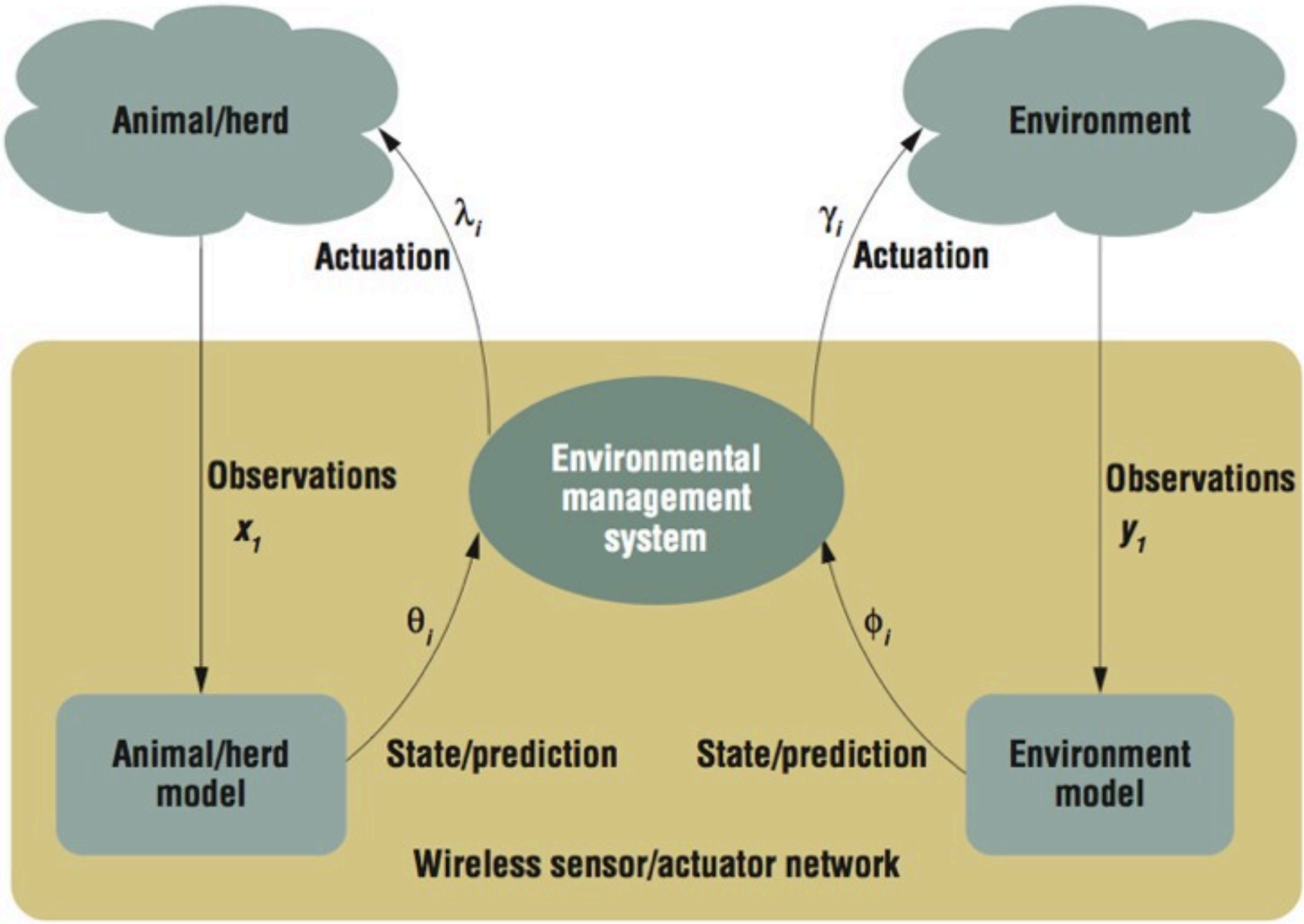
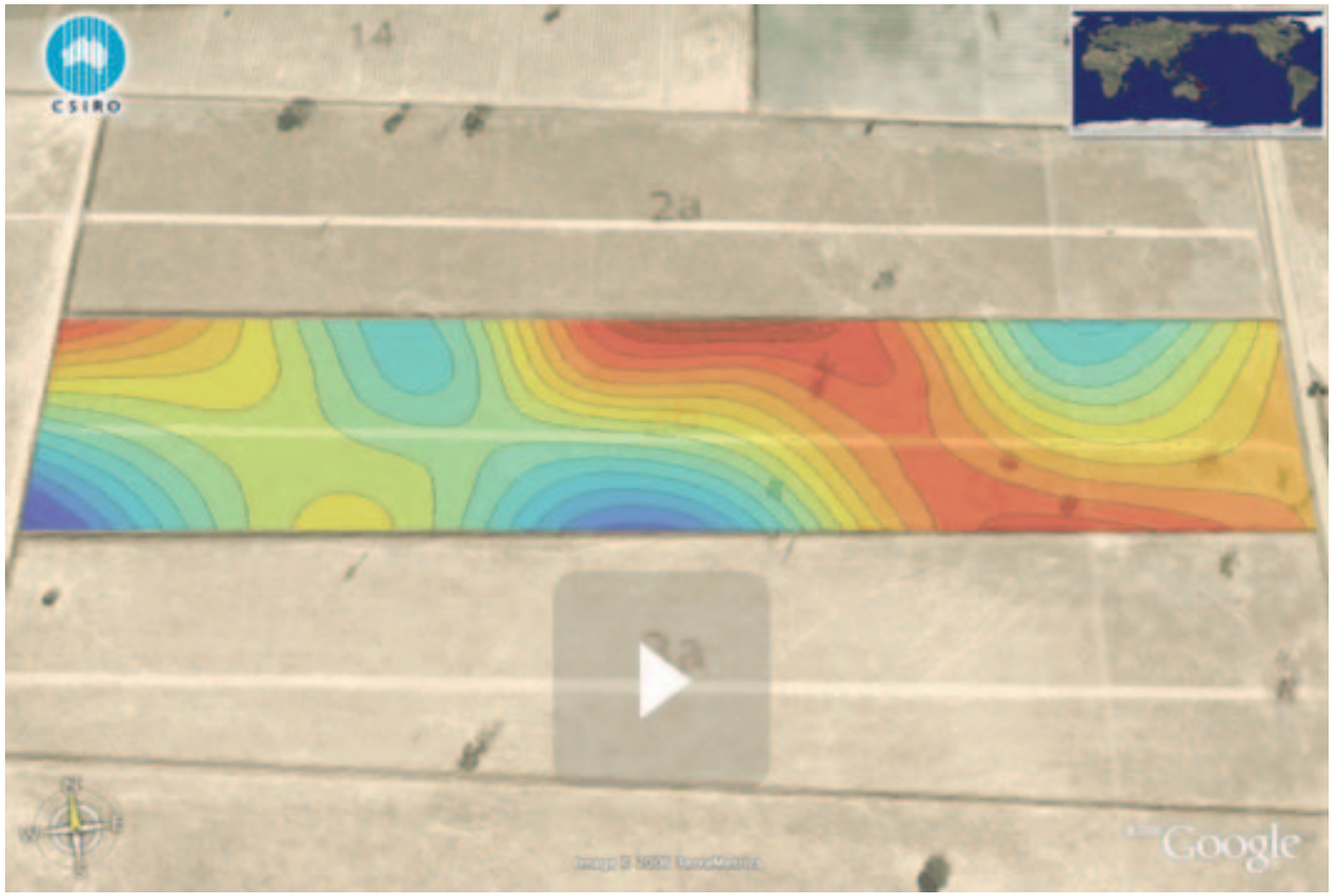
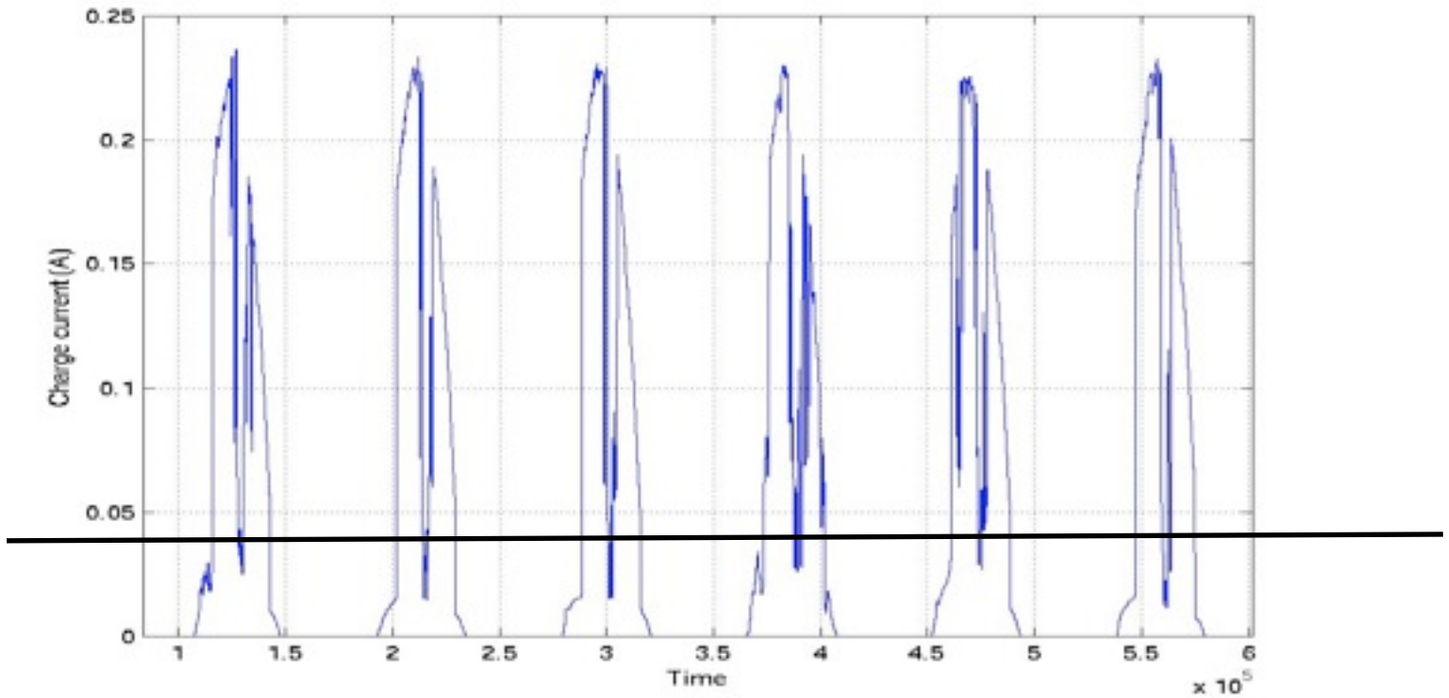
Animal agriculture: Closing the loop

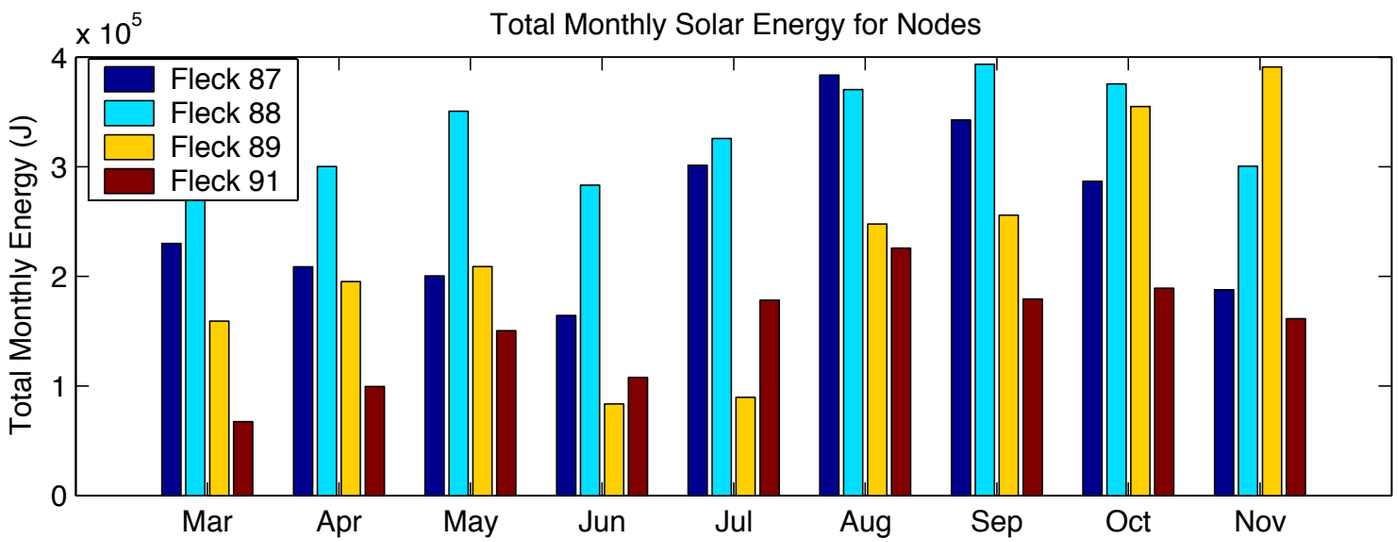


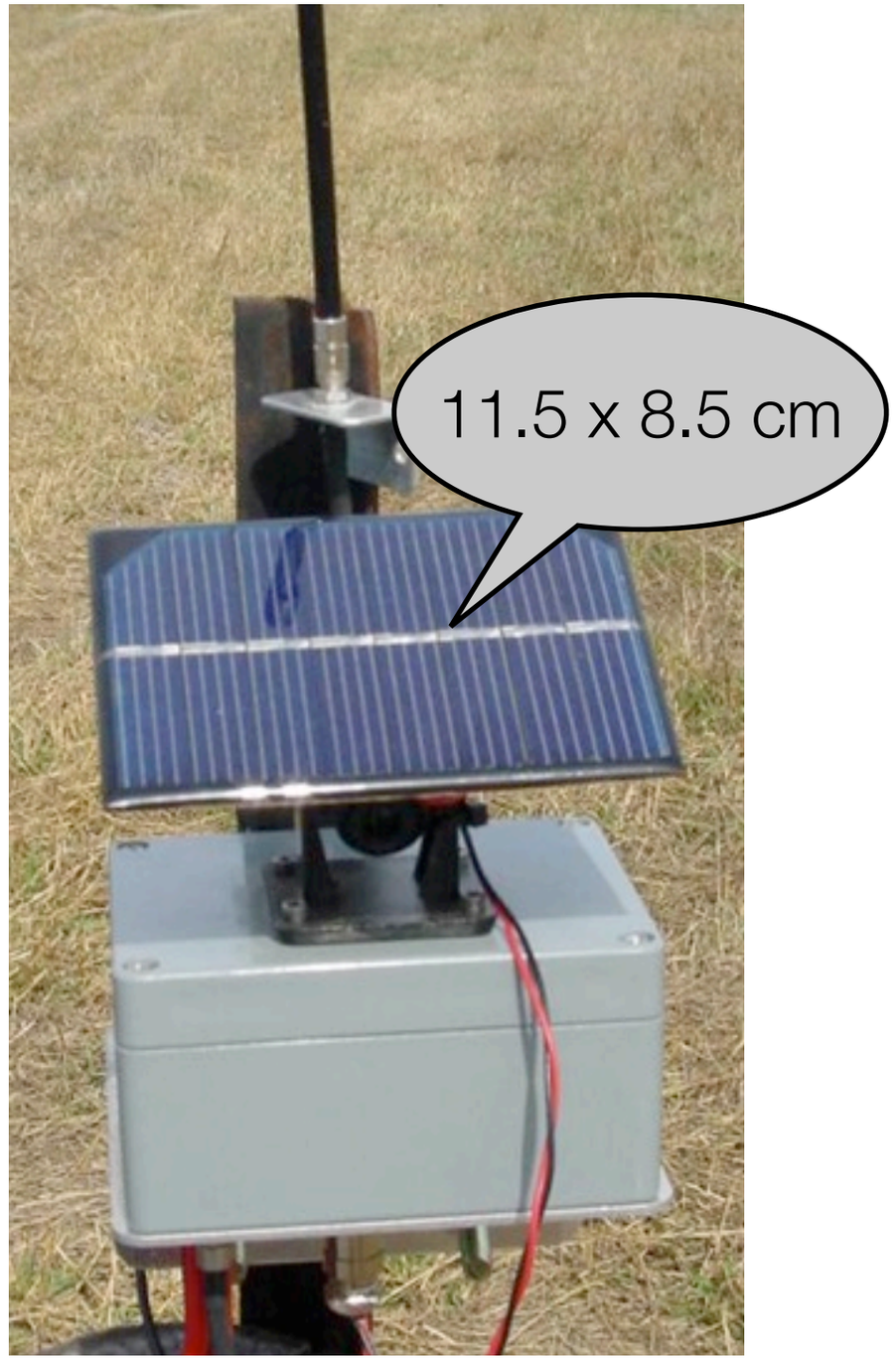
It all begins with moisture in the ground...

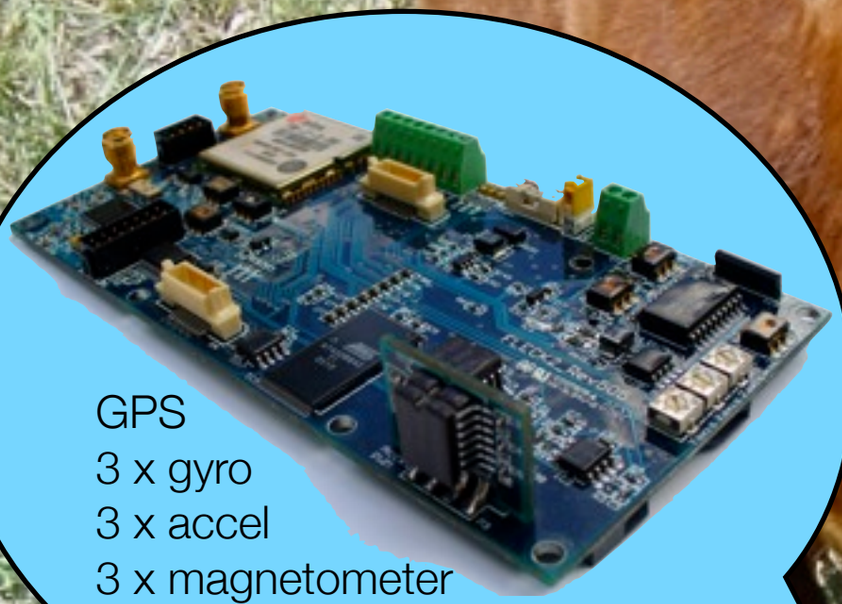


Solar power supply





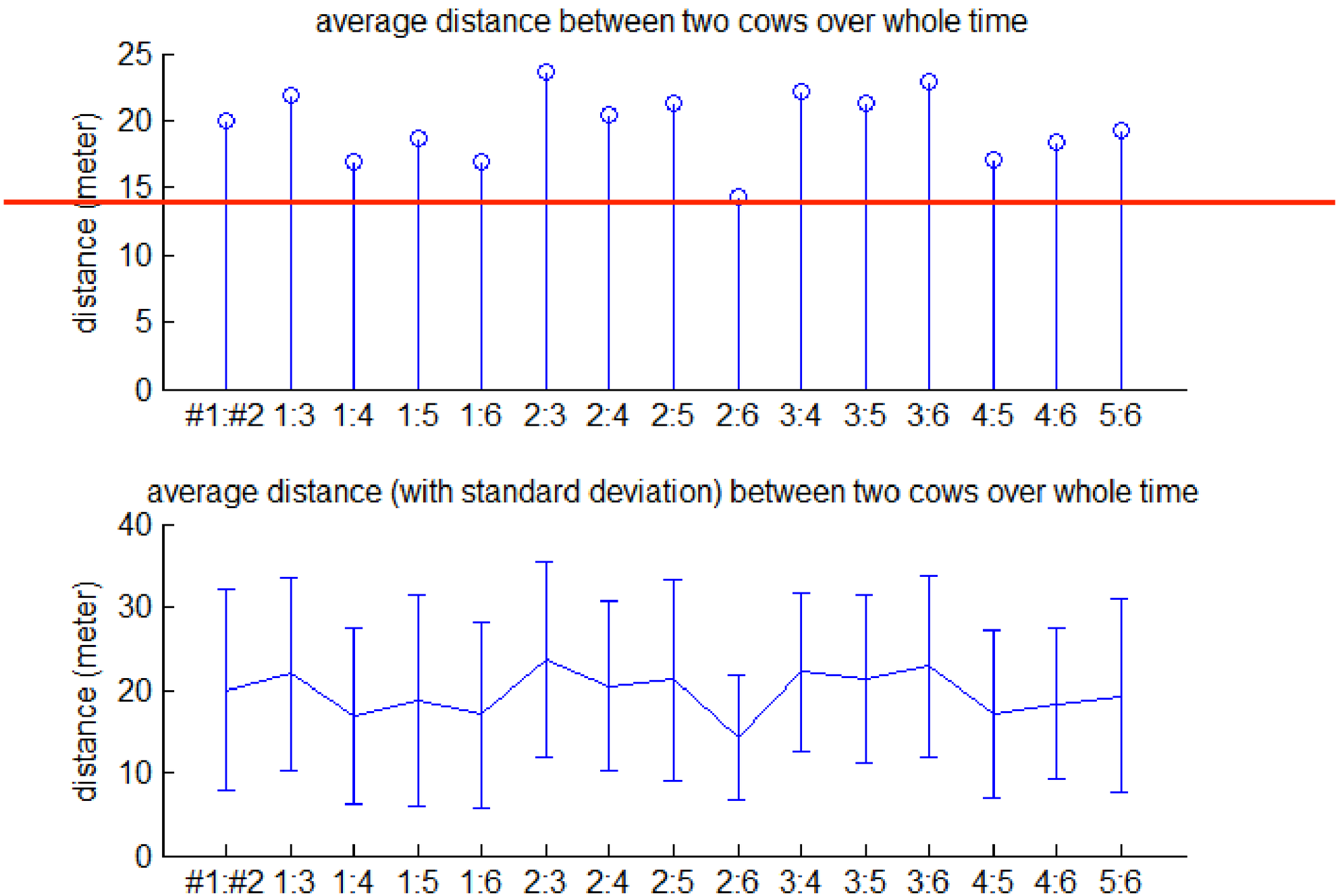




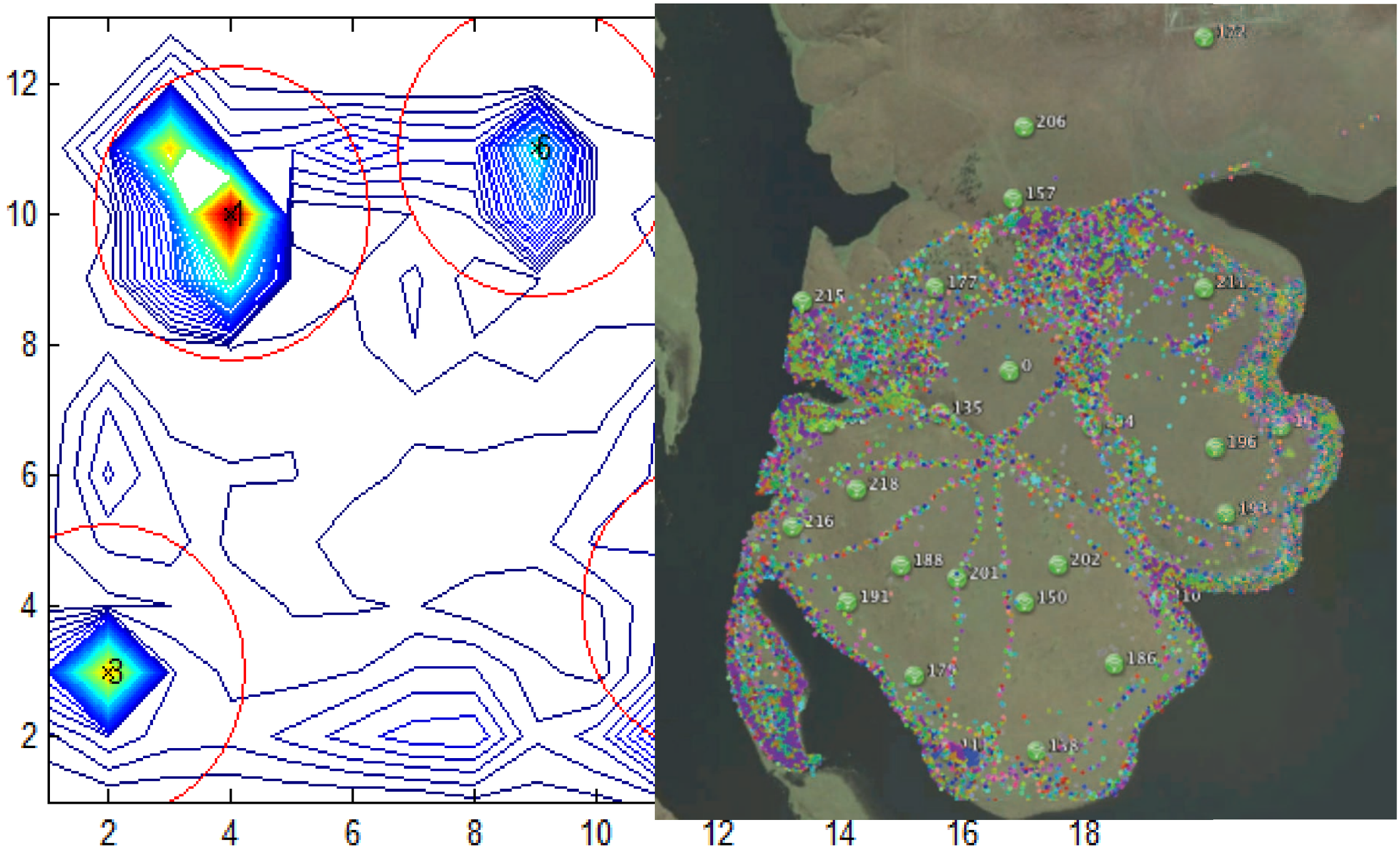
GPS
3 x gyro
3 x accel
3 x magnetometer

Animal position

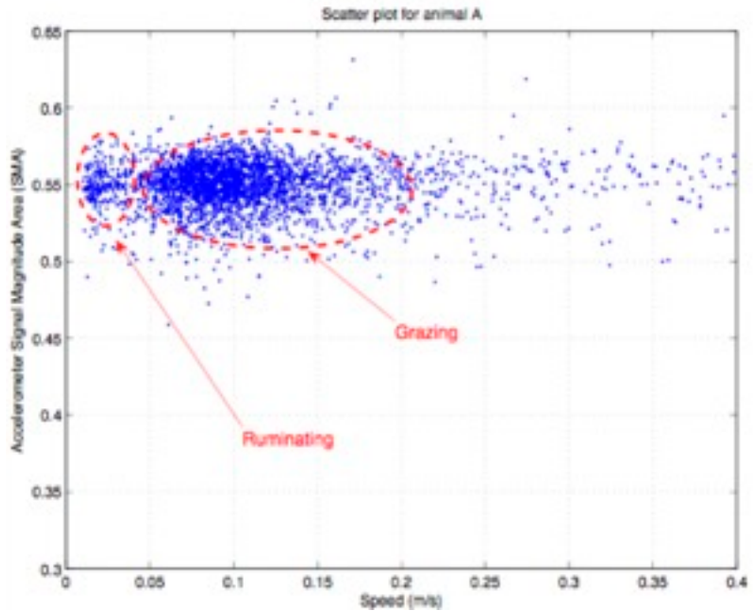
Animal proximity



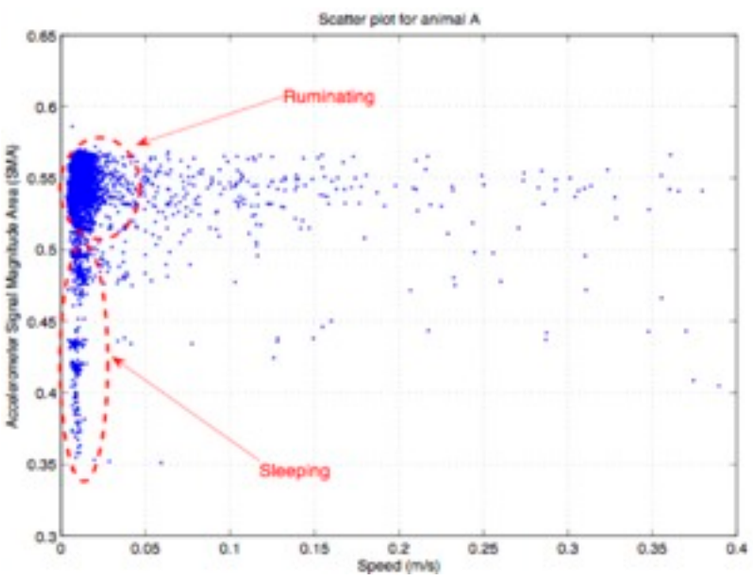
Pasture utilization



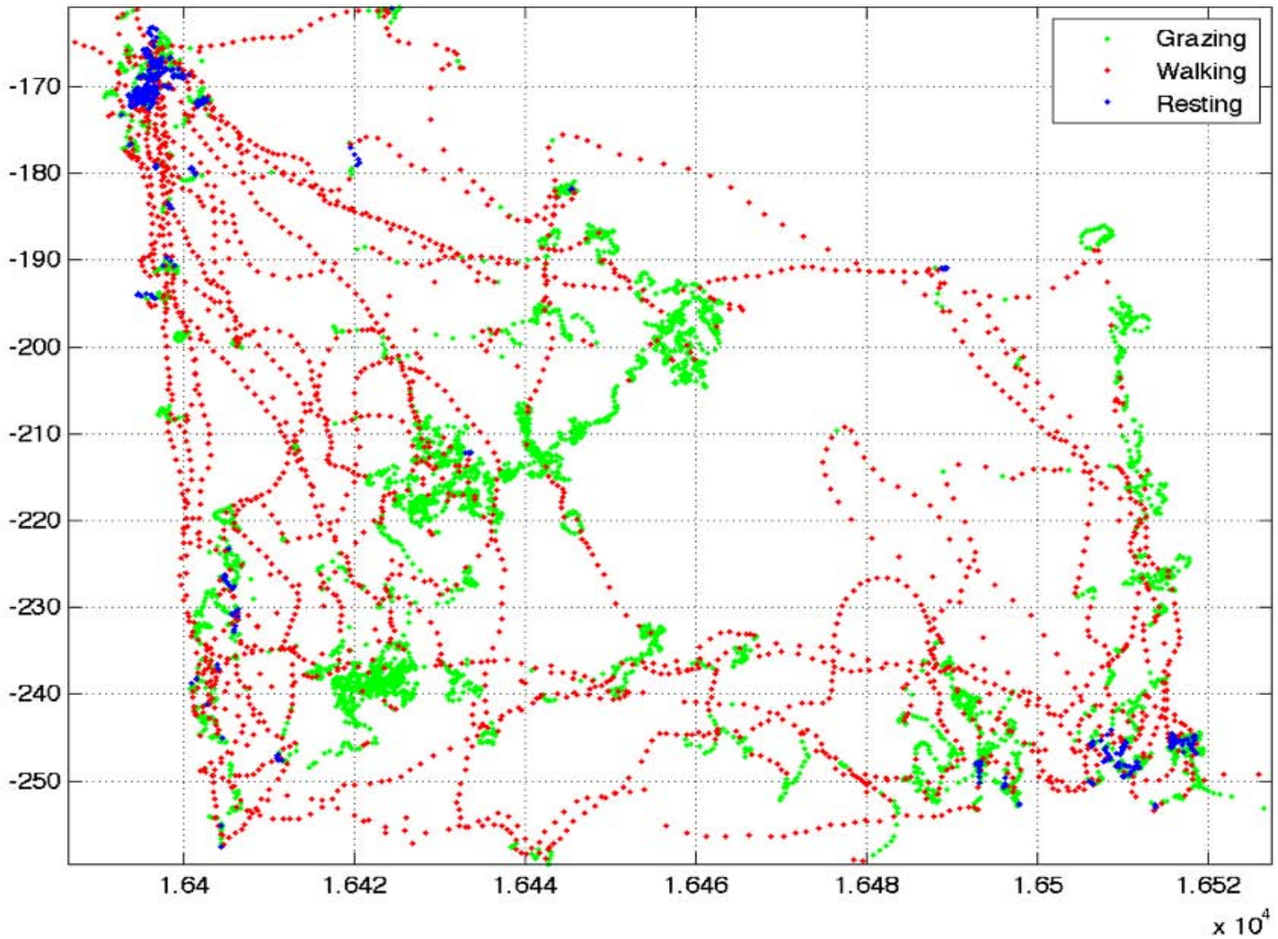
Spatial behaviour patterns



Day

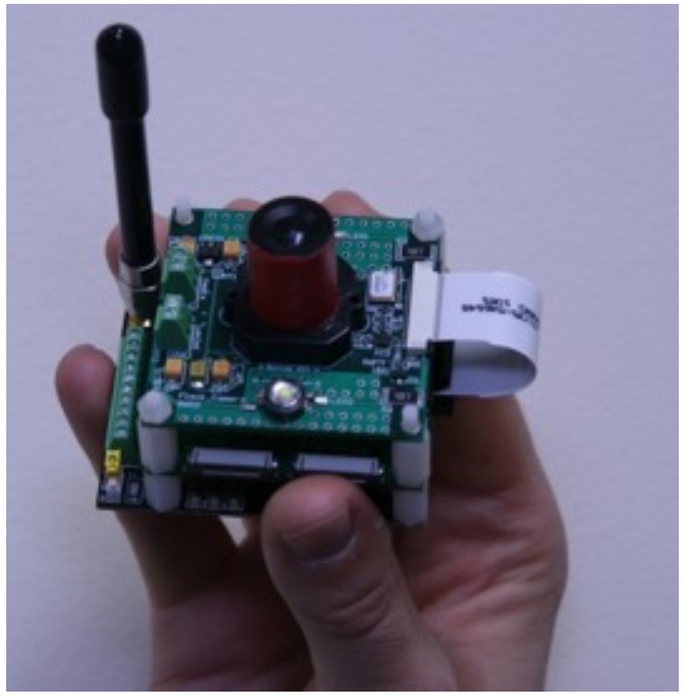


Night

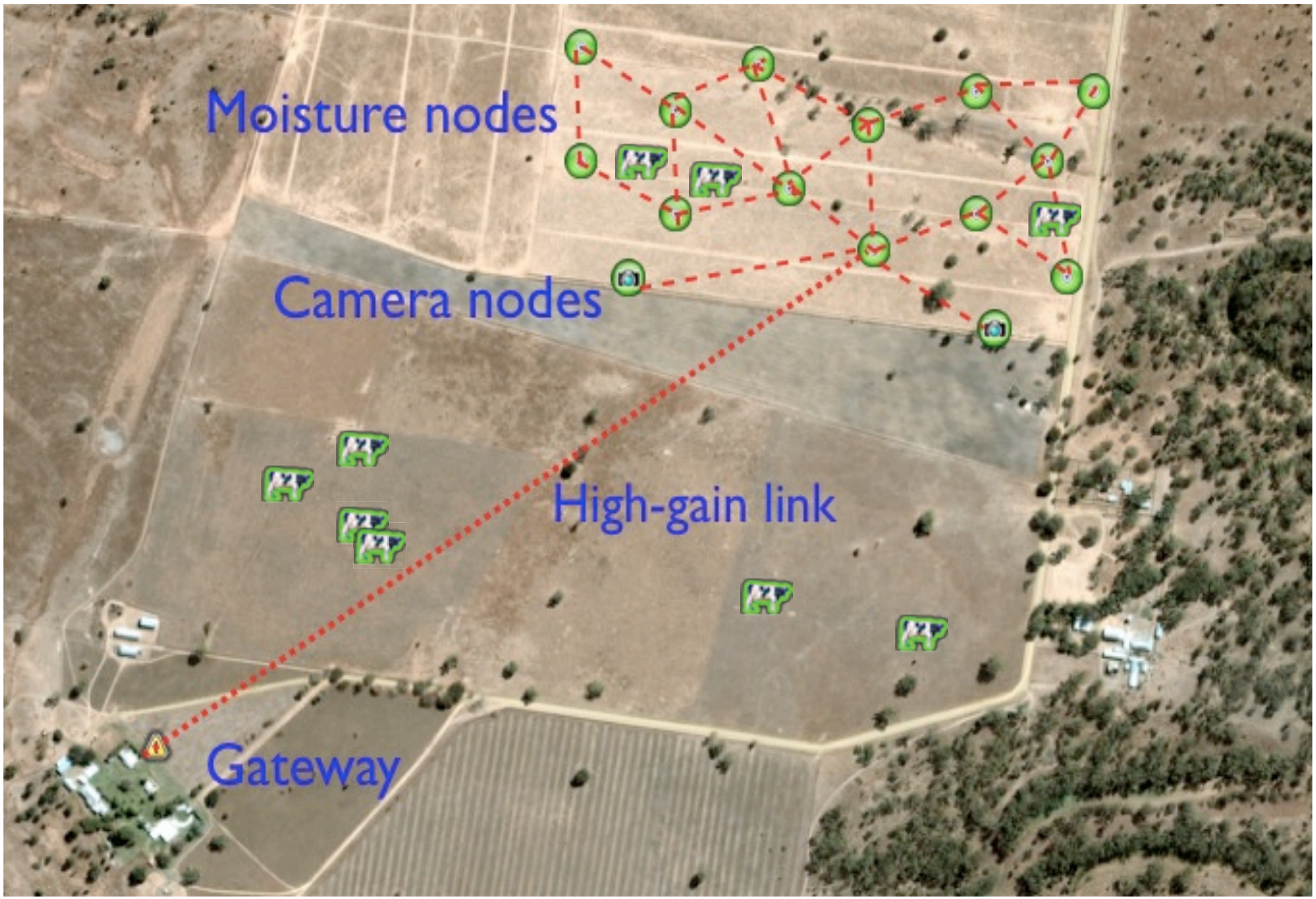


- New information for behavioural scientists
- Important information for new mobile routing protocols

Can we see what's going on?



Farm sensor network



Learnings

- ZTDMA worked poorly
- Struggled to keep our TOS port up to date with trunk development
- Software productivity and reliability was low
  - distance
  - over the air reprogramming not adequate
- Environmental housings were inadequate
- Batteries ruined by overcharging

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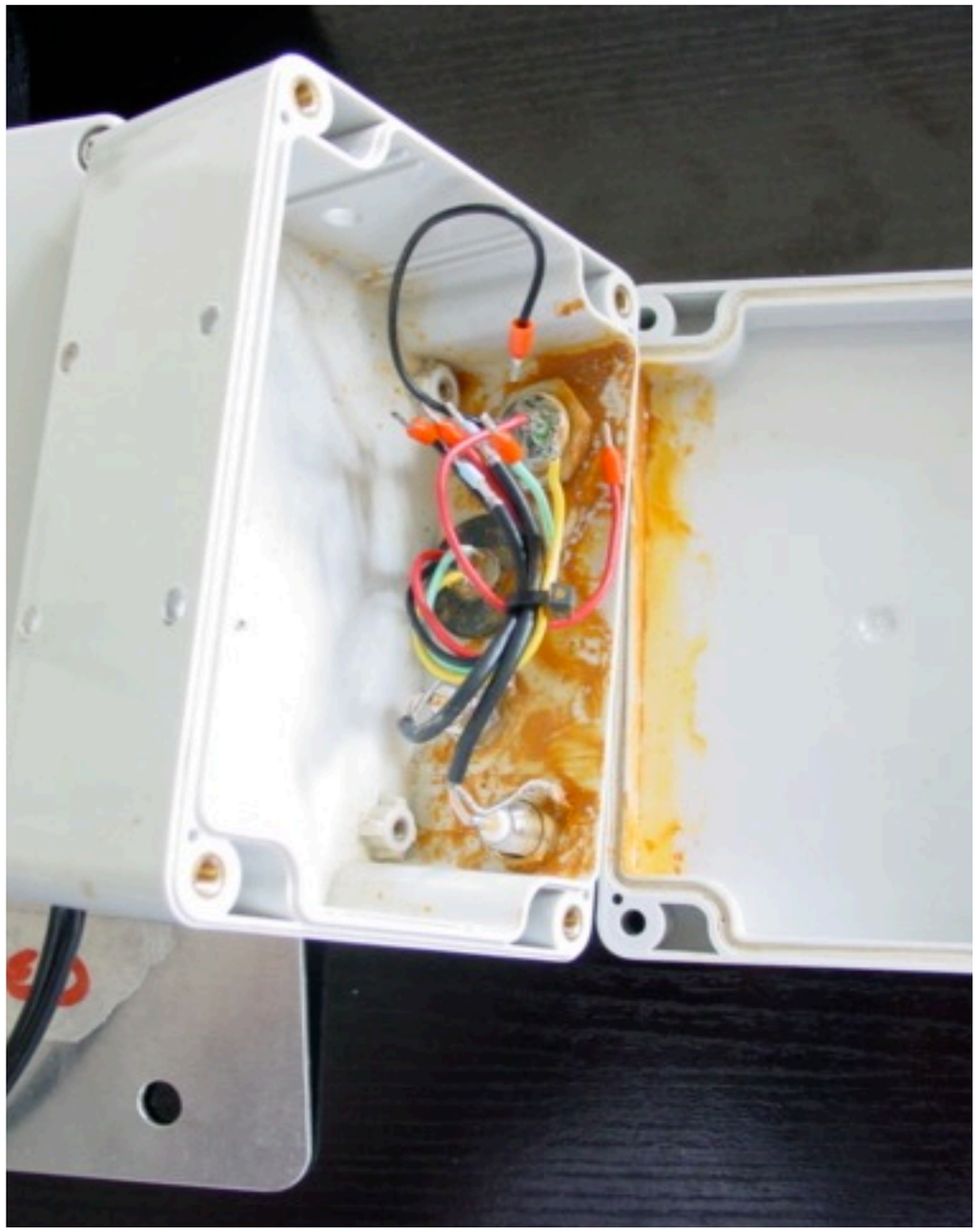
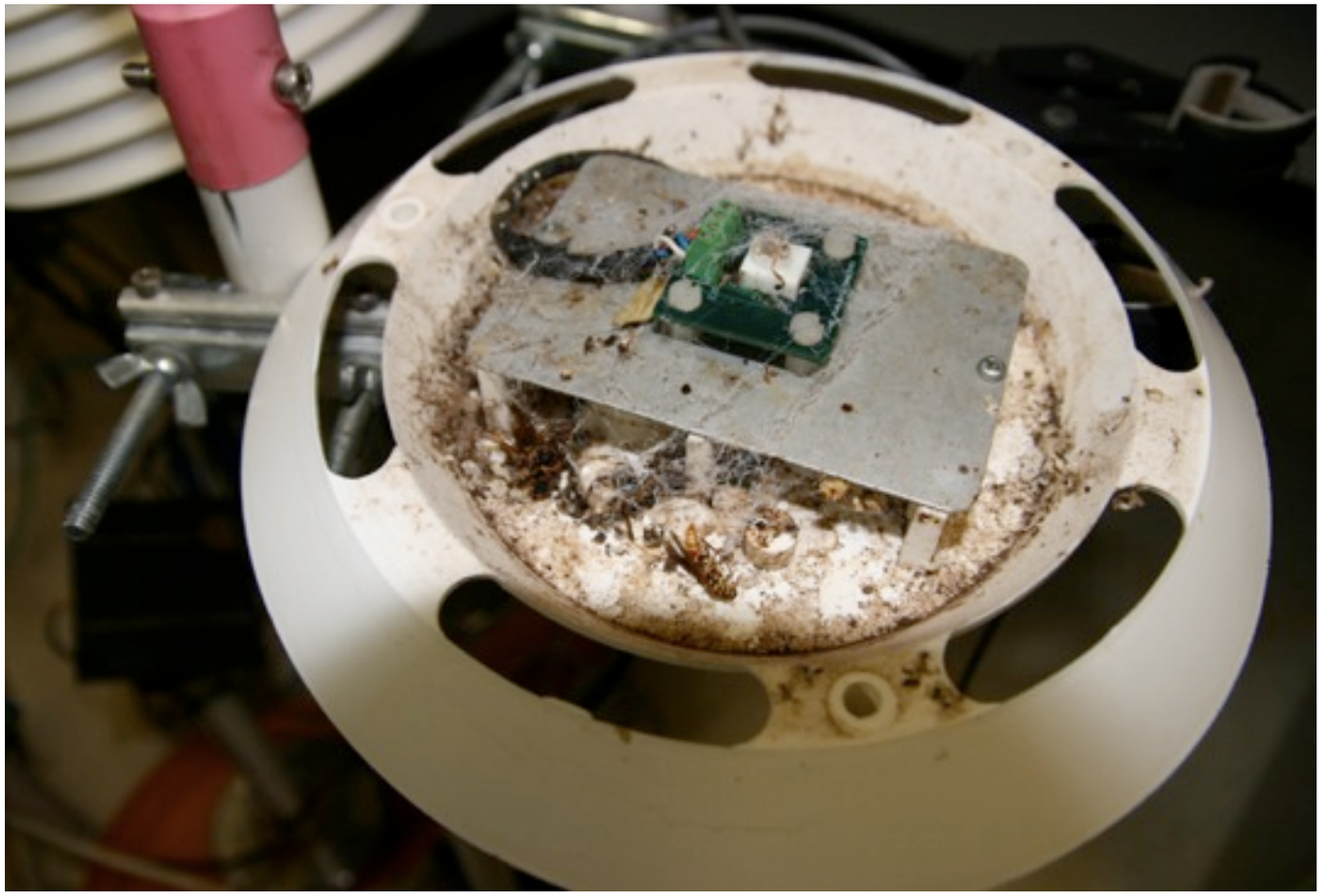
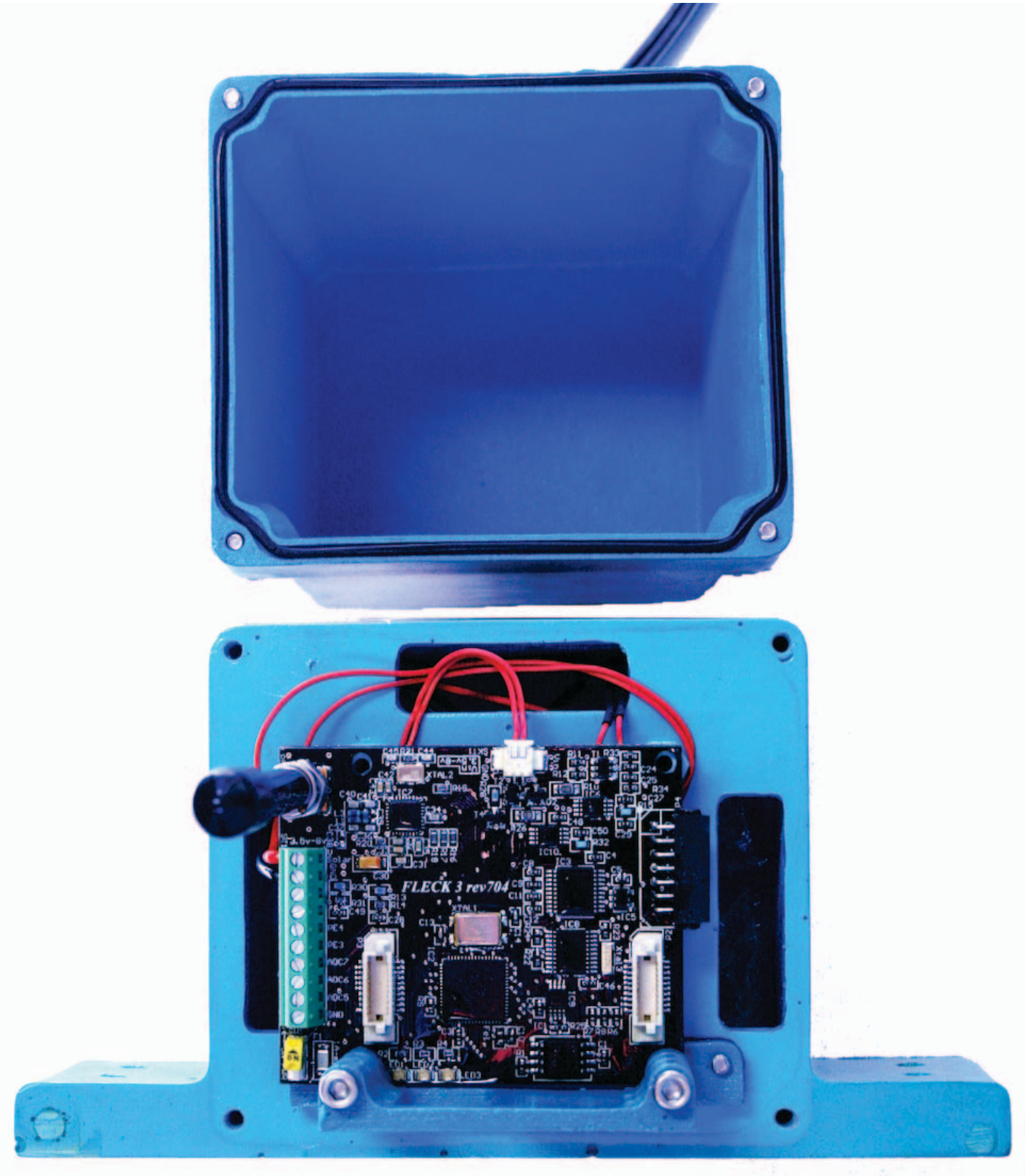
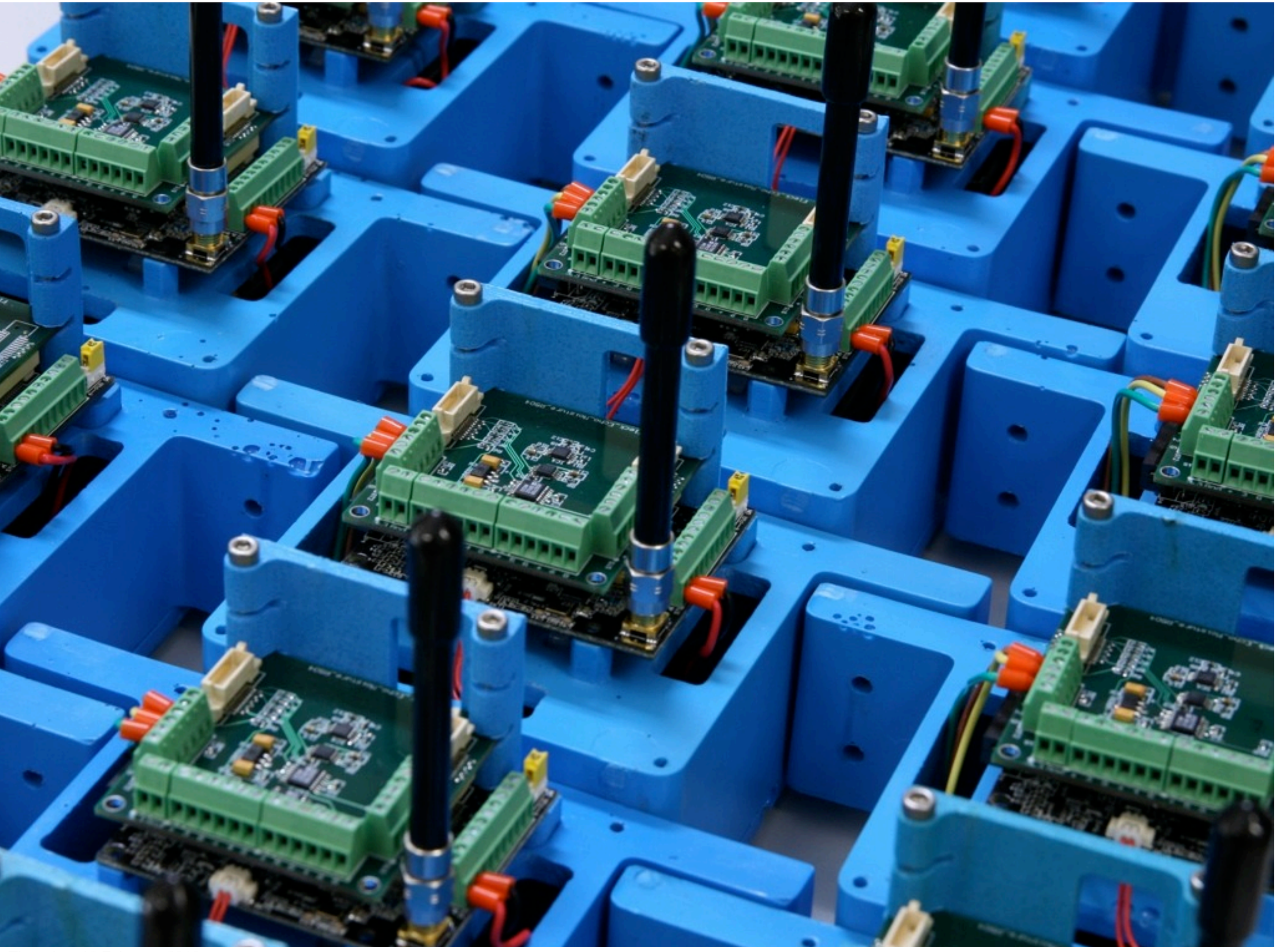




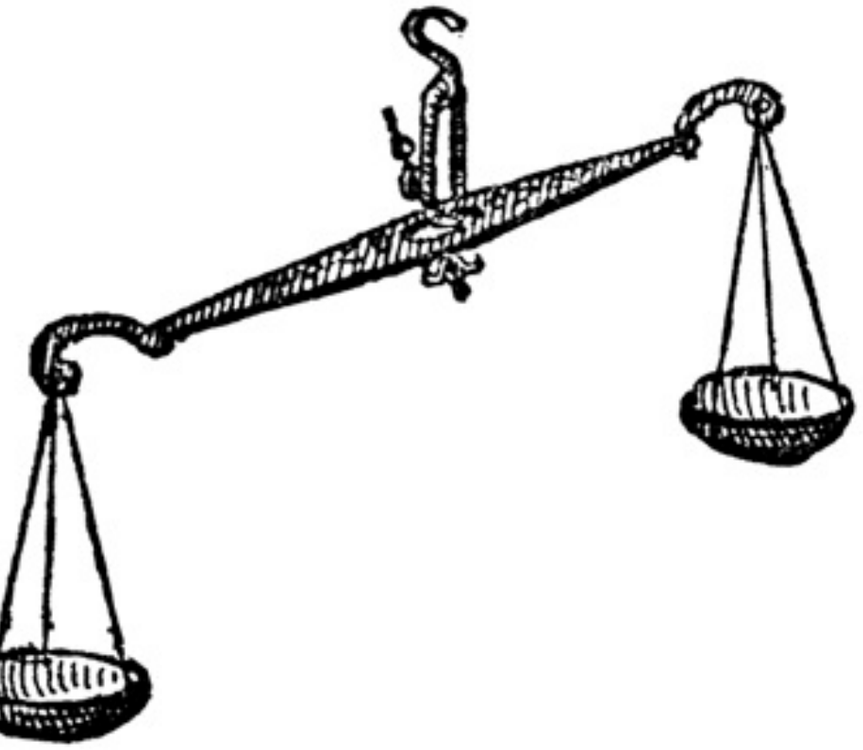

FLECK 3 rev704


CSIRO

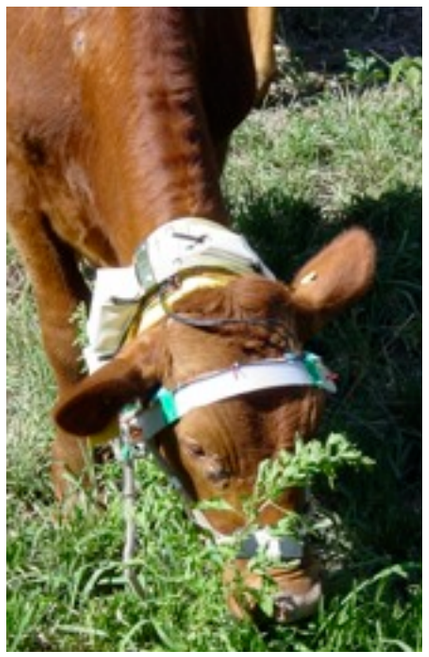


Events vs threads...

- What were we thinking ?
- Did we optimize the wrong thing?
- Memory size versus application development convenience
  - In the early days most people were developing small apps
  - Do we care about 1k vs 2k RAM usage if the chip has 4k RAM?
- We wrote our own tiny kernel with cooperative threading, static analyzer for thread sizing, crash dump analyzer etc.





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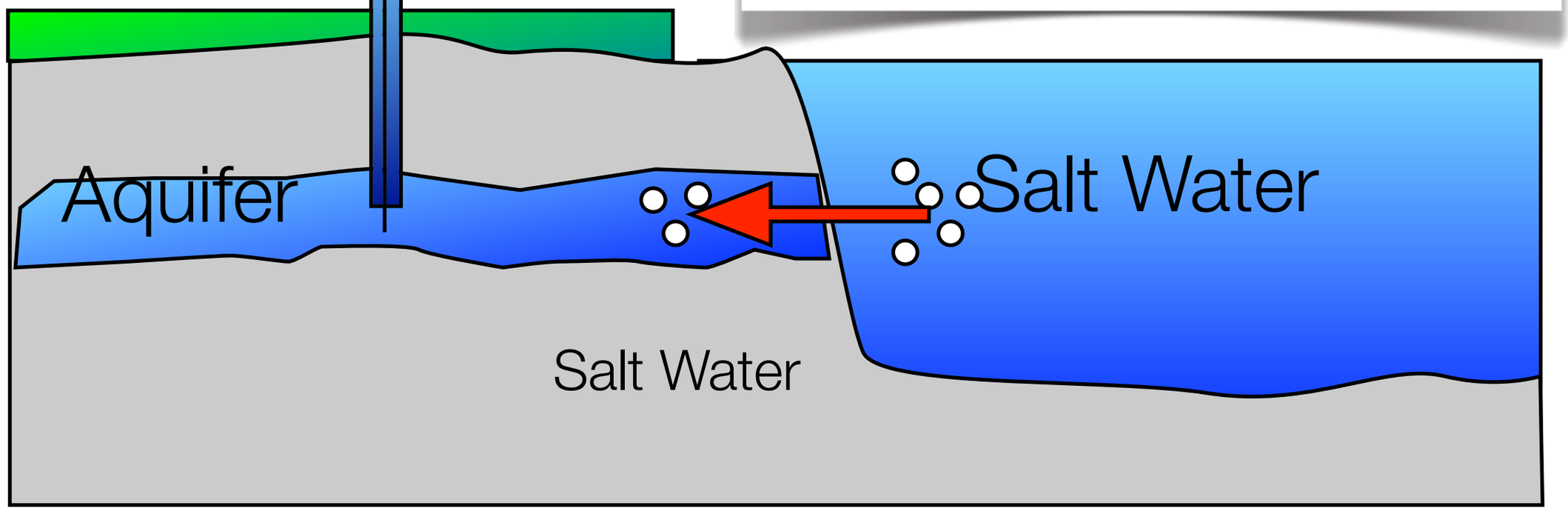
Fleck1C	Fleck2	Fleck3	Fleck3	Fleck3	Fleck3

Application: Salt Water Intrusion

Detect Salinity &

Stop Pumping

Pump Fresh



Learnings

- MintRoute worked well
- Radio survey is important.
    - Do the right radio survey!
- Channels really do vary (a lot!)
- An electrical storm can ruin an entire network

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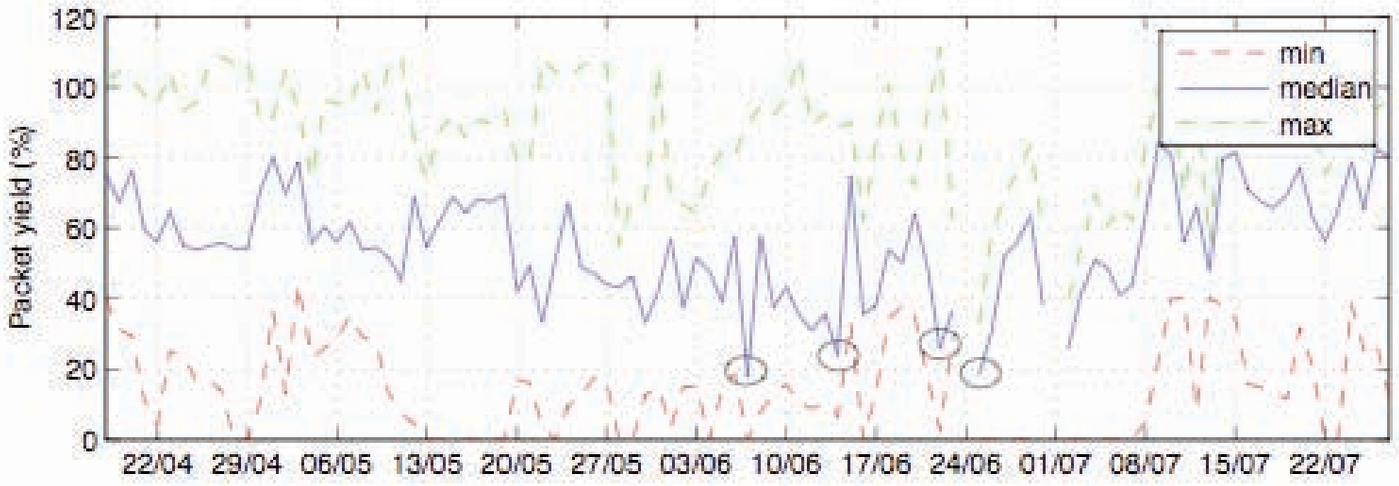
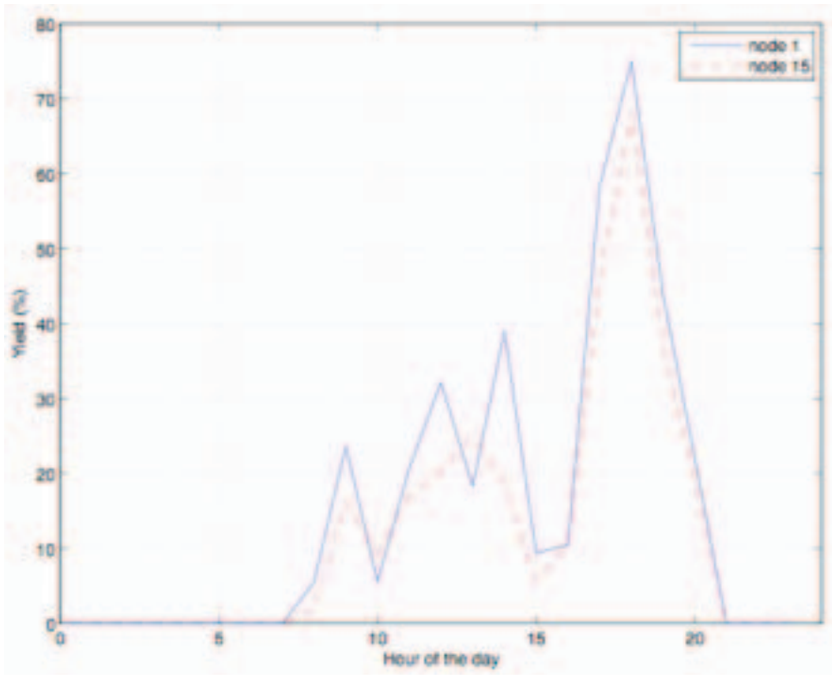
Temporal patterns in link performance





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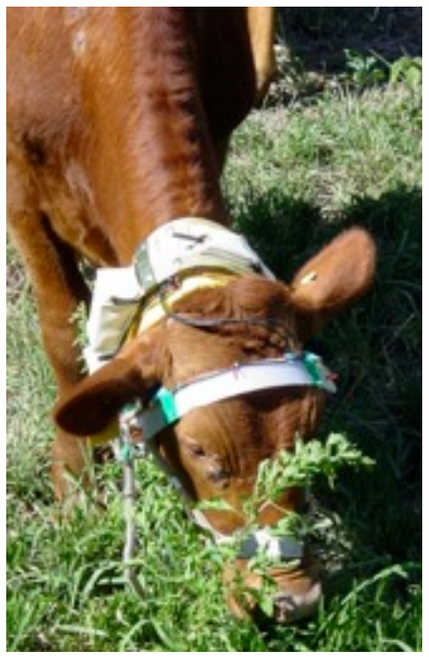

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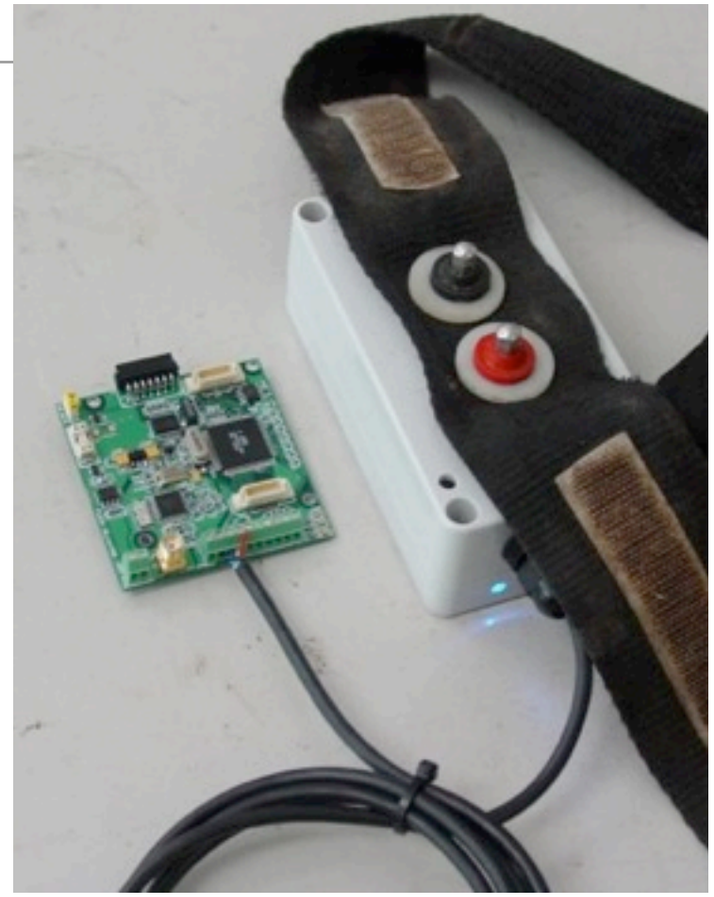
Animal welfare studies monitored animal heartrate and stress hormones

Animal control

- Exploit conditional learning
  - Cue (a sound)
  - Control (an electric shock)
    - Upto 1.5kV, cf. electric fences – 5kV
    - Like some dog collars

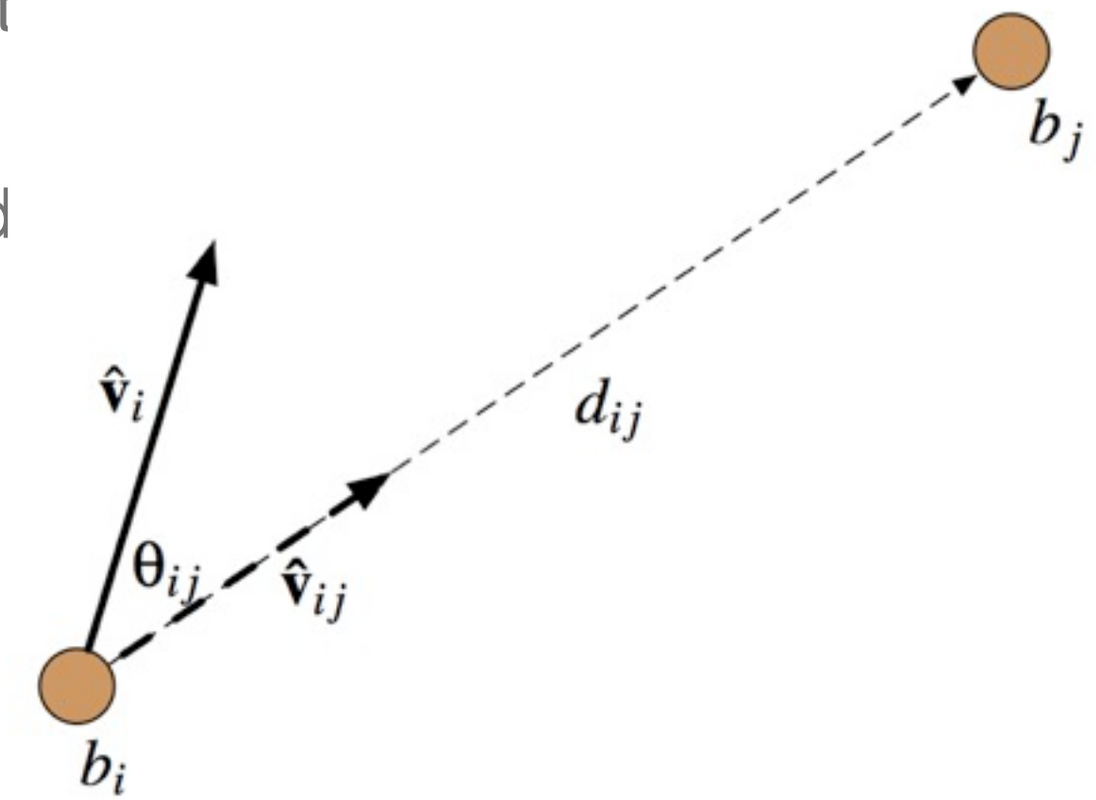


Domain problem: Bull separation

- Bulls are high value animals (up to $100,000 each)
- Serious challenges in preventing bulls from injuring each other

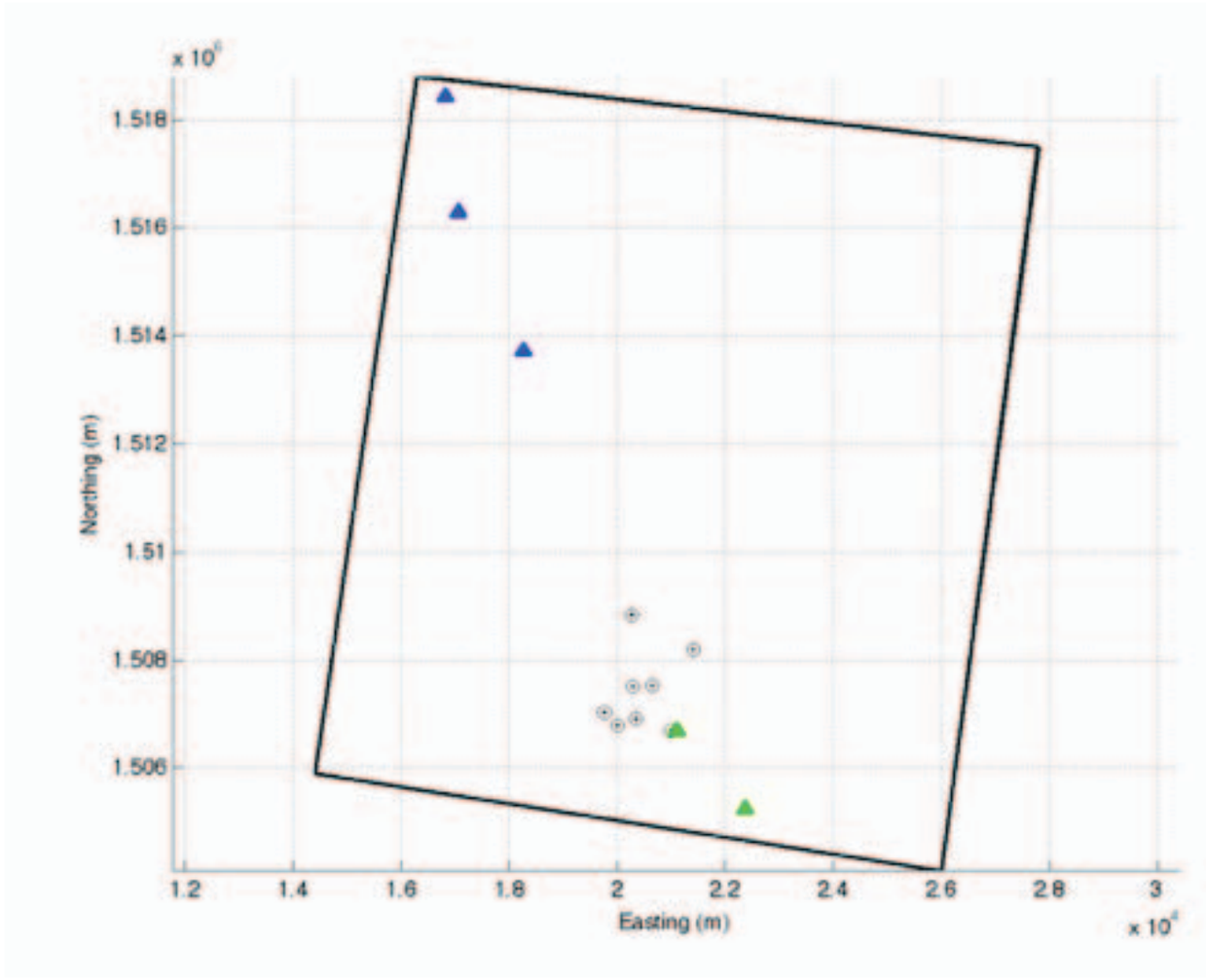
On-board processing

- Based on incoming beacons from other bulls and local information, each node can determine:
  - Distance from other bulls
  - Relative heading angle t
  - Projected speed toward



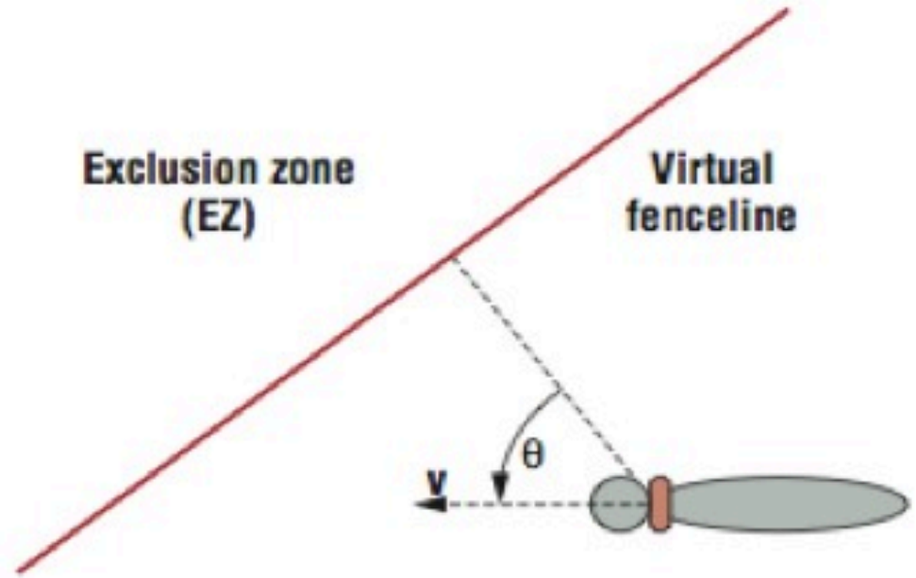
Bull separation

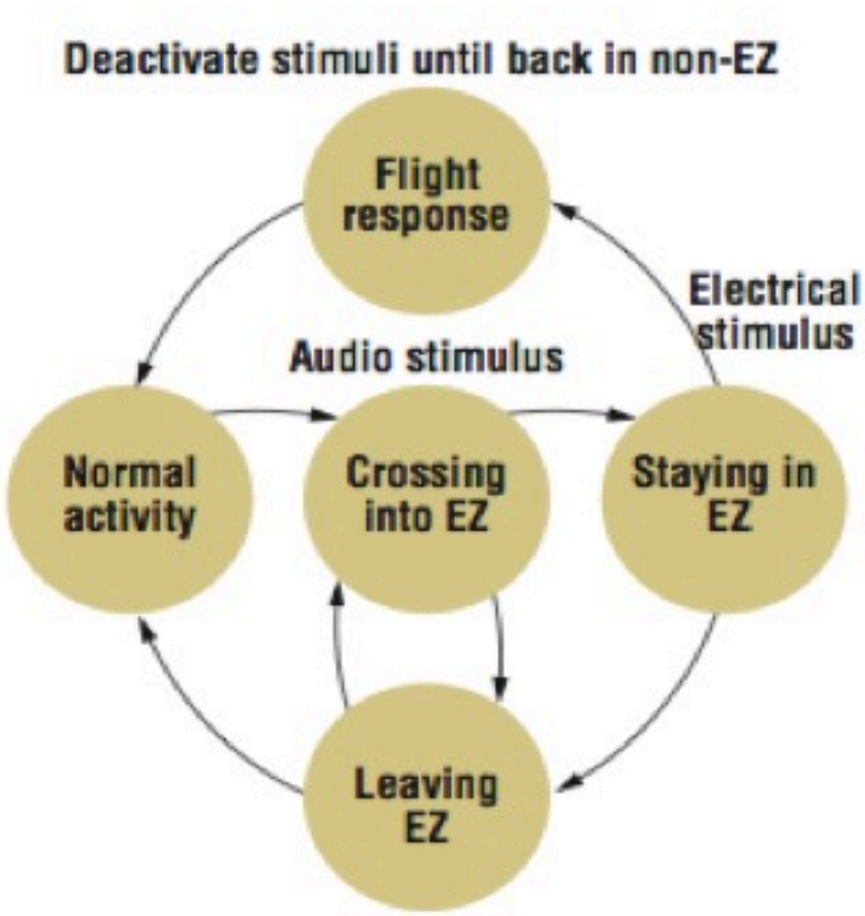
- Bulls in multi-sire paddocks fight and seriously injure each other
- Animal behaviour estimated by a peer-to-peer network
- Aversive stimulus applied to the aggressor



Virtual Fencing: Environmental Protection

- State of animal relative to virtual fenceline is used for spatial animal control



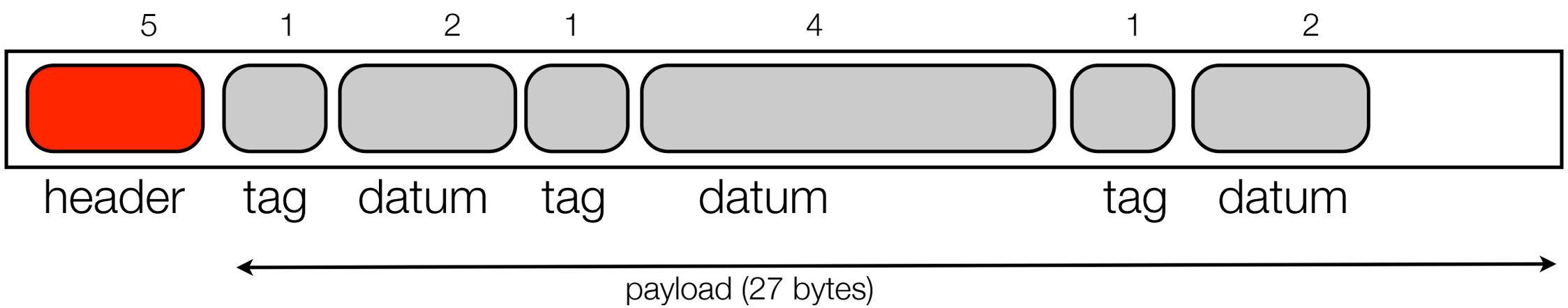


Virtual Fencing: Controlling spatial pasture utilization

Learnings

- Changing hardware and software at the same time is painful
- Good enough networking
- Code balance was changing
  - 12,000 lines of kernel (in C)
  - 23,000 lines of support code (in Python)
  - RPCs were showing their value
- Message formats got out of control

Self describing messages



Fleck 3 radio message

```
#include  "fos/tdf.h"


// update the packet payload

fos_tdf_clear();

fos_tdf_add_word(TDF_BATTERY_VOLTAGE, fos_power_battery_voltage() );
fos_tdf_add_word(TDF_BATTERY_CURRENT, fos_power_battery_current() );
fos_tdf_add_word(TDF_SOLAR_VOLTAGE, fos_power_solar_voltage() );

fos_tdf_flush();
```

Remote procedure calls

```
1       ret = rpc.power();
2       ret = ret[0];    # note
3       print "battery      %.2fV" % (ret.vbattery/1000.0)
4       print "solar cell   %.2fV" % (ret.vsolar/1000.0)
5       print "solar cell   %.2fmA" % (ret.isolar/1000.0)
```

Internet conected client call

Node-based service

```
include "fos/power.h"

power(uint16_t vbattery, uint16_t vsolar,
          uint16_t isolar <=  )
{

   vbattery = fos_power_battery_voltage();
   vsolar = fos_power_solar_voltage();
   isolar = fos_power_battery_current();

   return OK;
}
```

actions/power.rpc

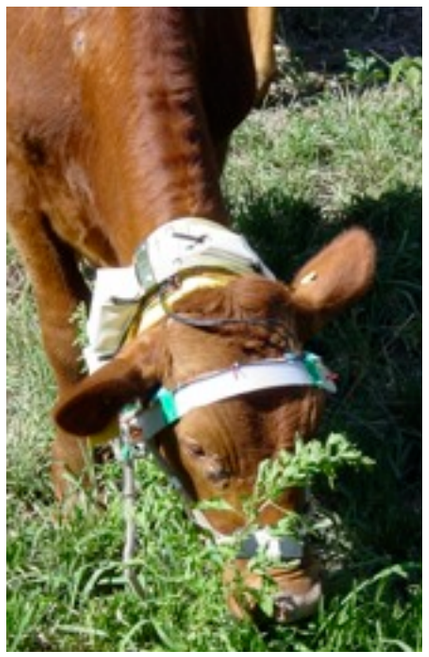
Some standard services

`kernel`	get FOS system memory statistics
`leds`	set or toggle LEDs
`power`	get battery and solar cell status
`rtc_get`	get time from the real-time clock
`rtc_set`	set the real-time clock
`temp`	get temperature from the onboard sensor
`adc`	return value from specificed ADC channel
`threads`	get information about threads, label and stack usage
`txpwr_set`	set radio transmit power
`reboot`	reboot the node
`read_eeprom`	read from EEPROM
`read_ram`	read from RAM
`write_eeprom`	write to EEPROM
`write_ram`	write to RAM

A simple shell

```
1  ratbert % fosmon.py --addr 7
2  Connecting to listener localhost:9001 ...
3  Connected to node 7  (h for help)
4  fosmon@7 --> volts
5  battery     3.52V
6  solar cell  3.74V
7  solar cell  0.02mA
8  fosmon@7 --> temp
9  temp     29C
10 fosmon@7 --> mem
11 free memory 2875 bytes
12 fosmon@7 --> q
13 ratbert %
```



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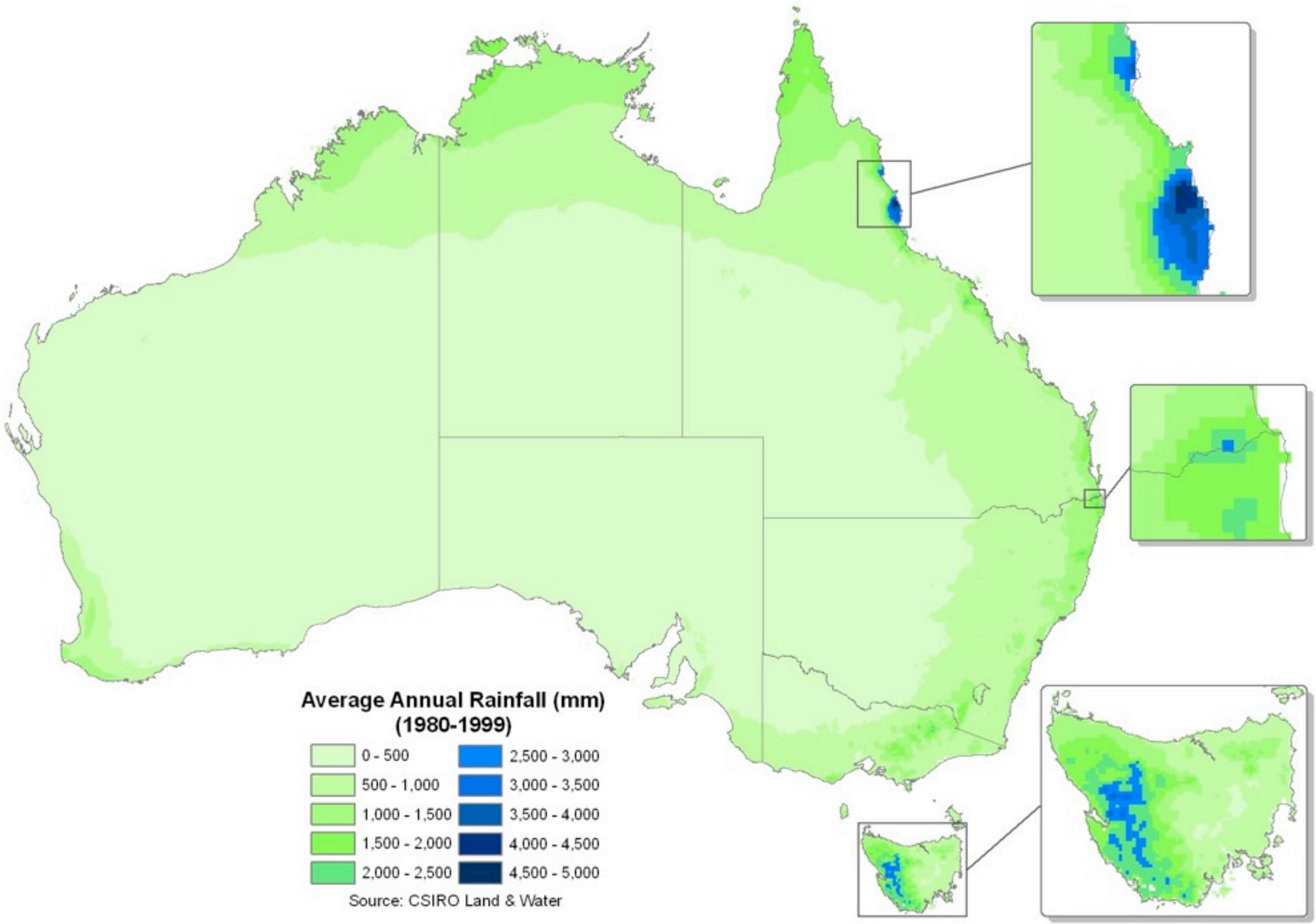
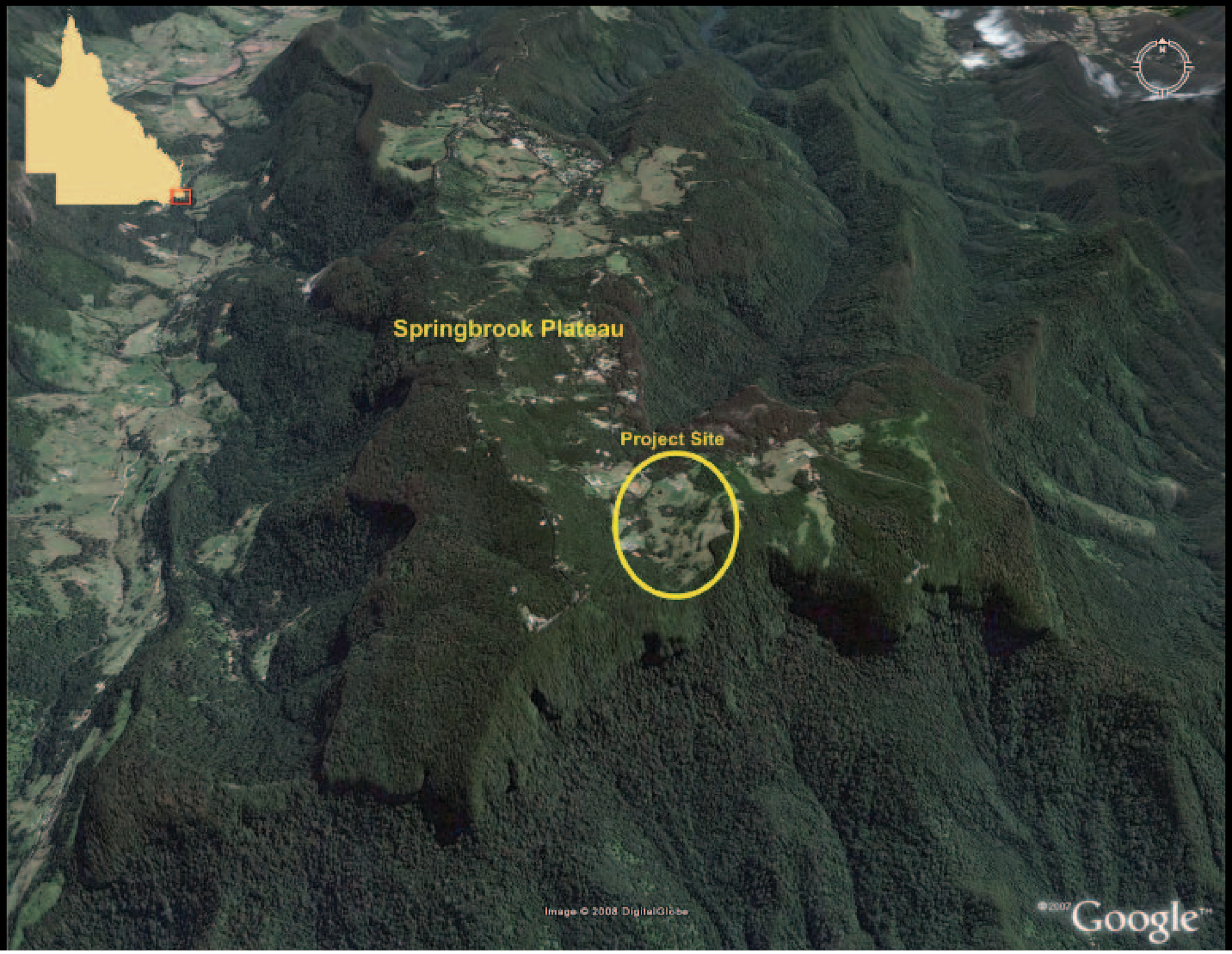
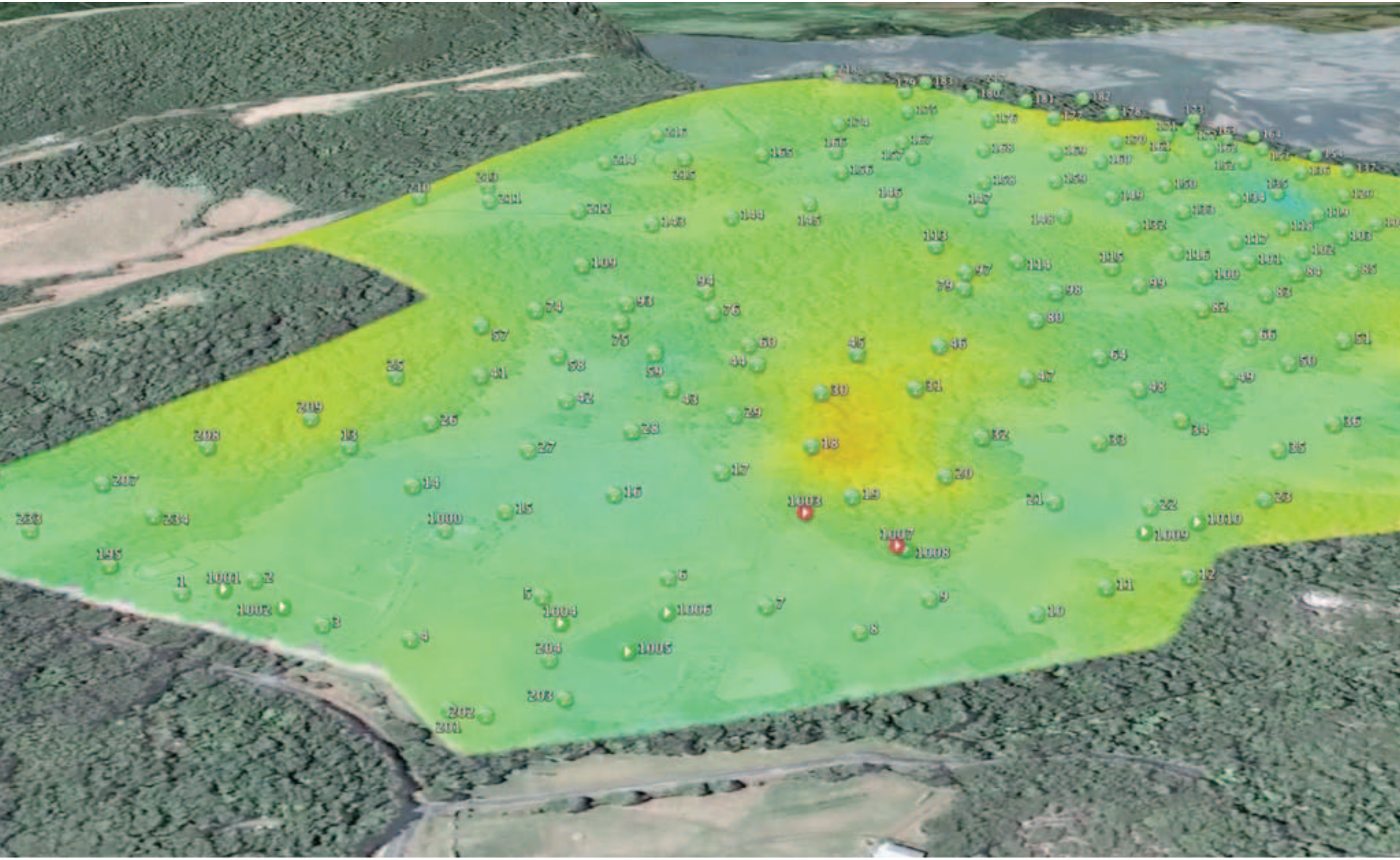

Average Annual Rainfall (mm)
(1980-1999)
0 - 500
500 - 1,000
1,000 - 1,500
1,500 - 2,000
2,000 - 2,500
2,500 - 3,000
3,000 - 3,500
3,500 - 4,000
4,000 - 4,500
4,500 - 5,000
Source: CSIRO Land & Water

Wireless Sensor Networks (Springbrook)

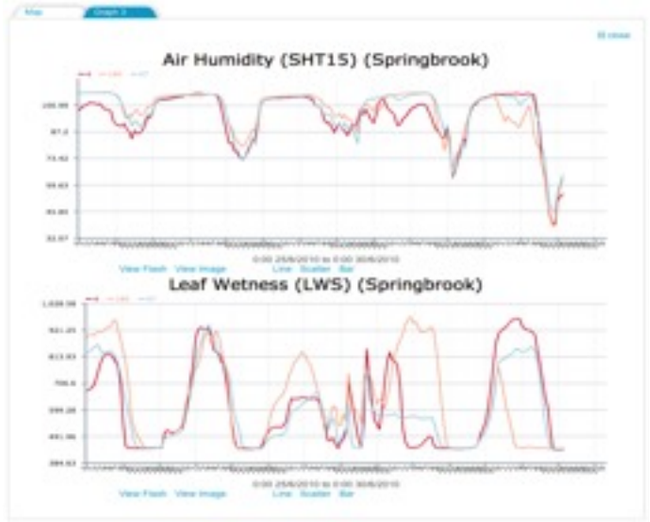


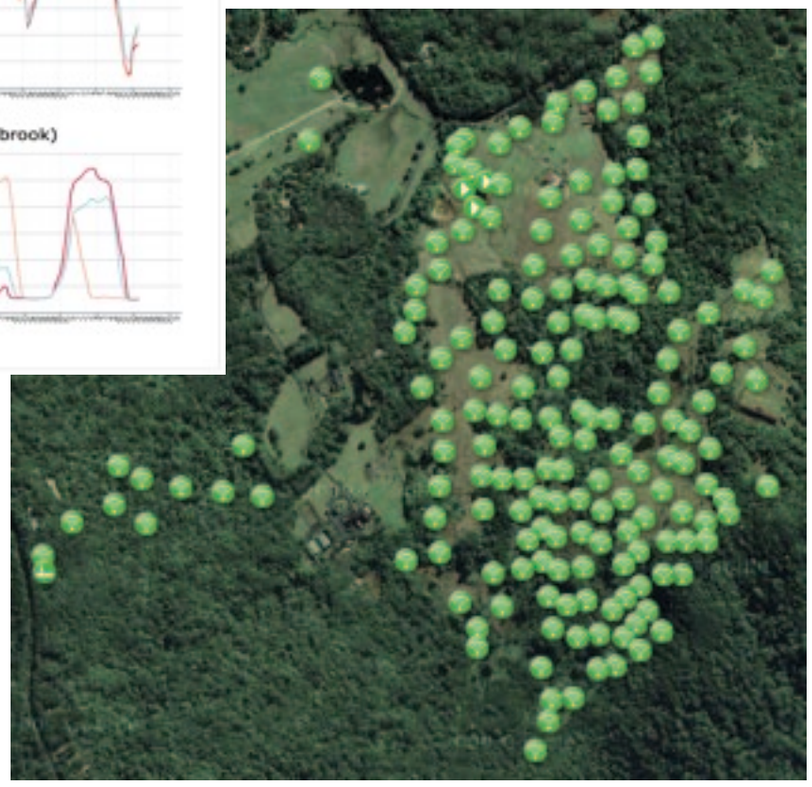


www.sensornets.csiro.au

Restoration Ecology - Springbrook

- 175 microclimate nodes
  - 642 environmental sensors
  - 5 min sample period
  - ~250,000 samples per day
- 10 “multimedia” nodes
  - Acoustic / image capture
  - Compute acoustic biodiversity metric





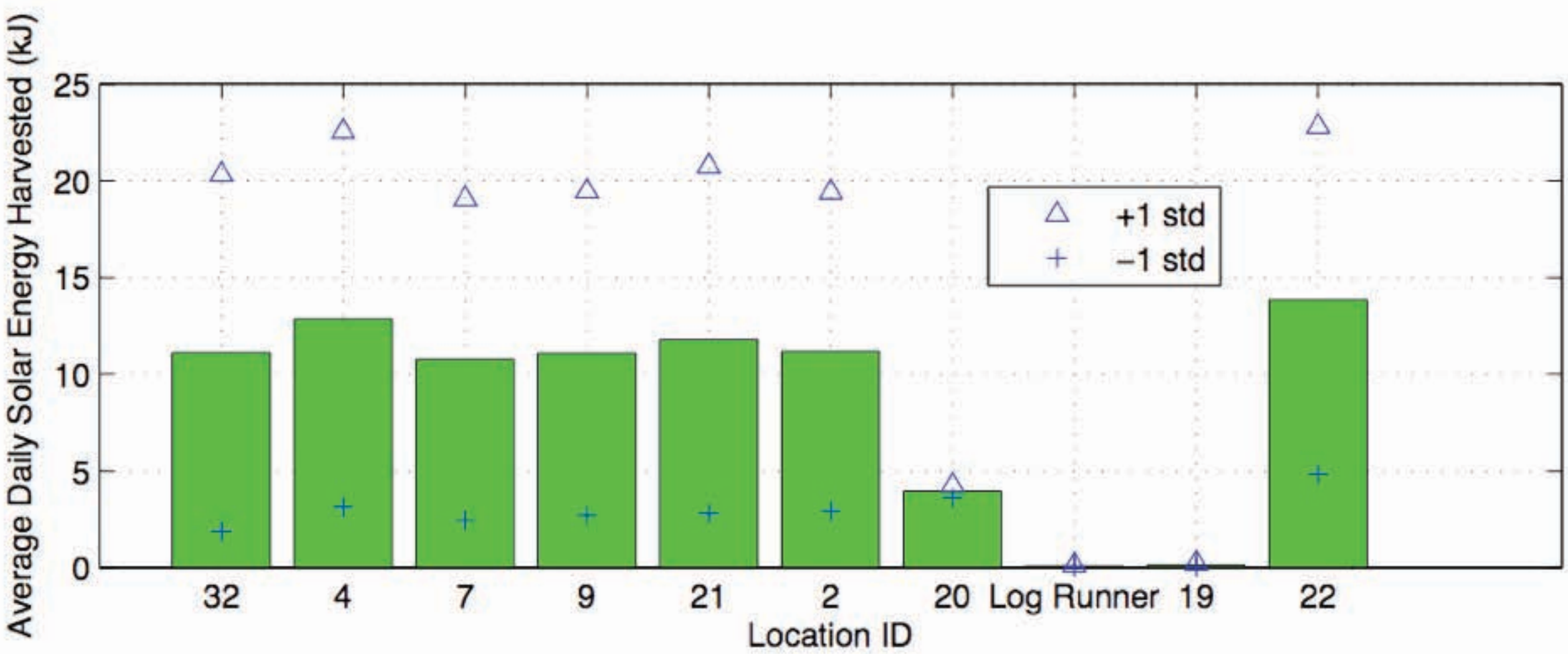
Queensland Government

Learnings

- Radio propagation is poor through dense wet forest
- Not much solar energy in a dense forest
- Is “deploy and forget” realistic or misguided?

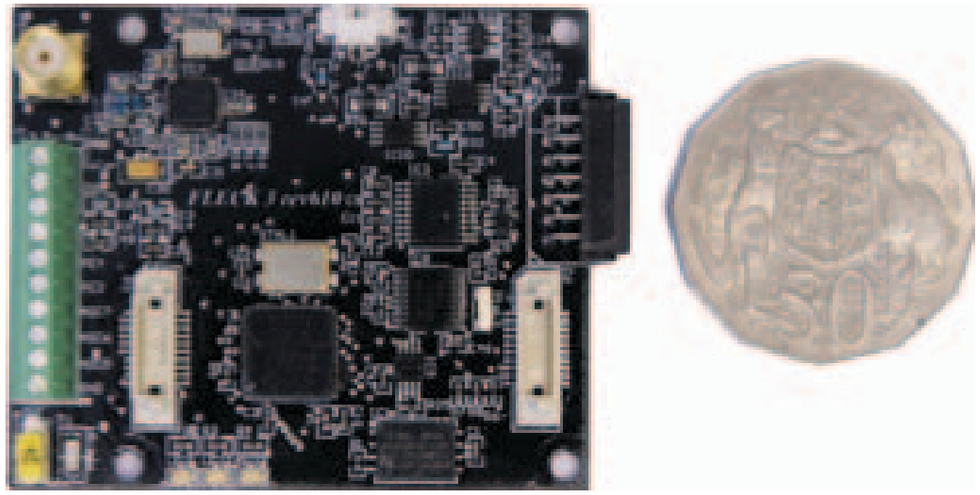
> *“Ubiquitous computing’s dream of wireless sensors everywhere is accompanied by the nightmare of battery replacement and disposal”*
>
> *— Paradiso and Starner.*

Energy harvest

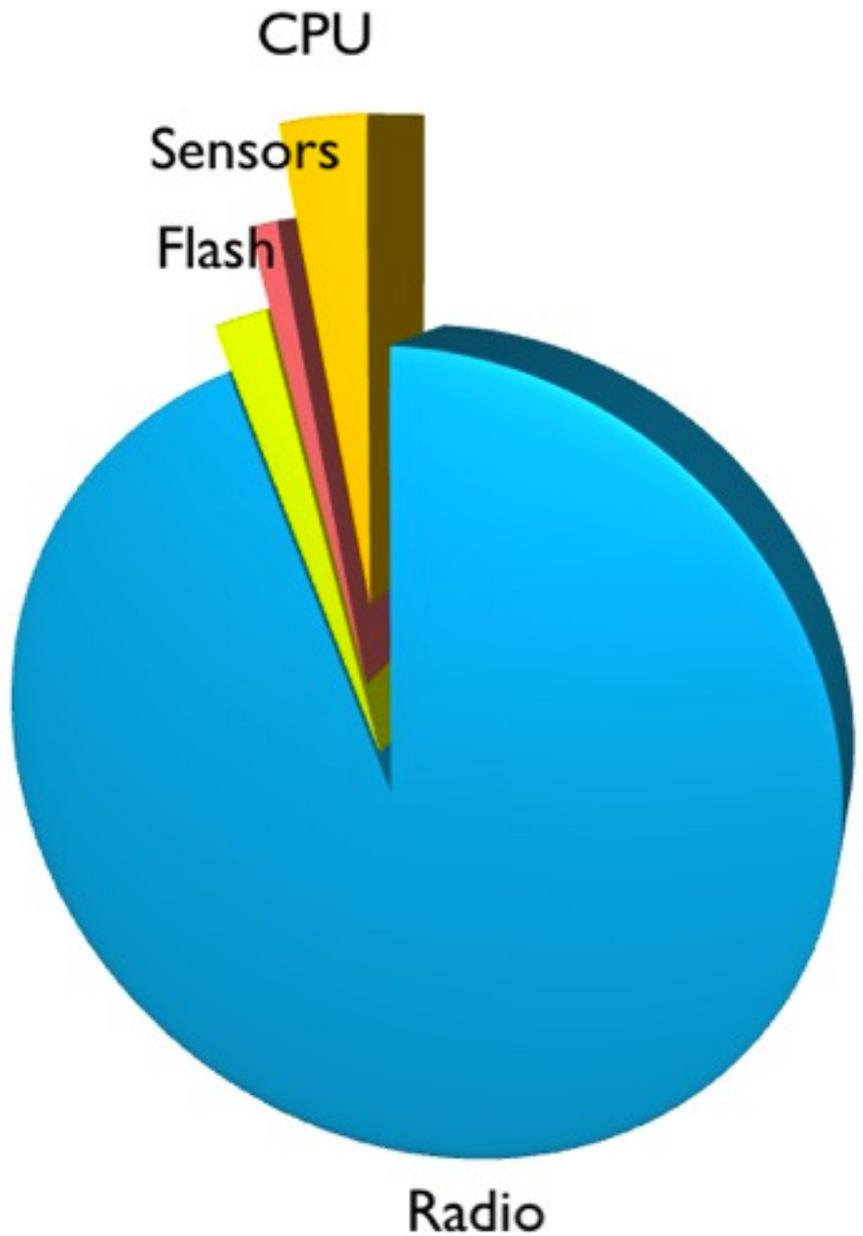


Energy consumption

- "Traditional" Wireless Sensor Network (WSN) node:
  - Sample-and-send operation
  - Low-power sensors (e.g. temp/humidity)

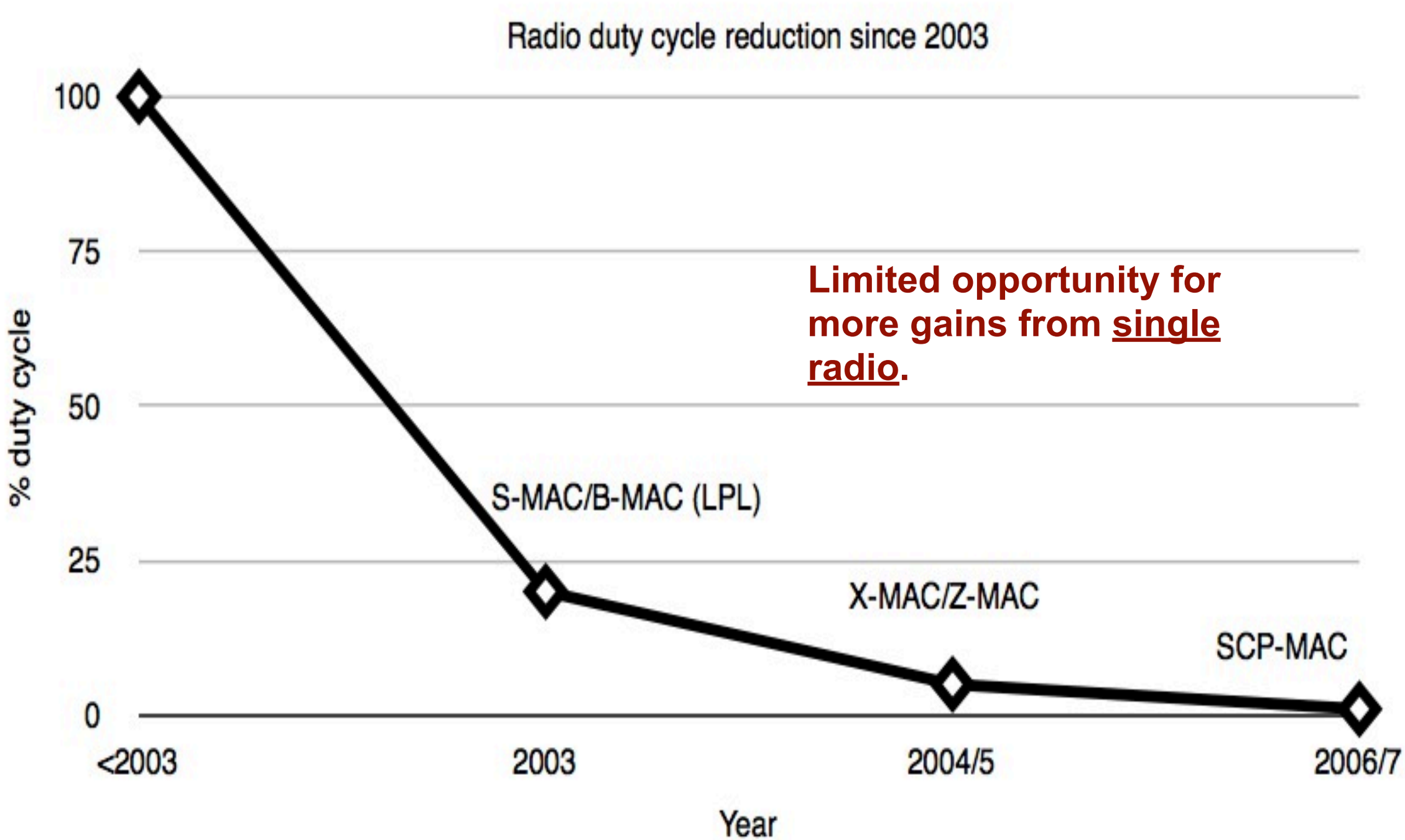


"Mote" class device



- Key research question:
  - How can we significantly **reduce energy** being consumed by **radio**?

Duty-cycle radio



Limited opportunity for more gains from single radio.

Learnings

- Radio propagation is poor through dense wet forest
- Not much solar energy in a dense forest
- Is “deploy and forget” realistic or misguided?

Security

- The thing we never speak of...

- Issues
  - Confidentiality
    - ➡ message content is private
  - Identity
    - ➡ we really know who sent it

- Symmetric cyphers are cheap, but have the key exchange problem

- Assymmetric (public key) cyphers are expensive (to achieve strength)

Exploiting commodity crypto technology

- Cheap: cost < USD4.5
- Small: 6.1 × 9.7 mm, less than 2% of area of Fleck

```
1  /* trustedFleck public key collector. */
2  uint8_t fos_tpm_getPubKey(uint8_t *pubKey);
3
4  /* Asymmetric key encryption/decryption. */
5  uint8_t fos_tpm_encryption(uint8_t *msg, uint16_t len,
6                             uint8_t *pubKey, uint8_t *cipher);
7  uint8_t fos_tpm_decryption(uint8_t *cipher, uint8_t *msg,
8                             uint16_t *len);
9
10 /* Digital signature and verification. */
11 uint8_t fos_tpm_sign(uint8_t *digest, uint8_t *signature);
12 uint8_t fos_tpm_verifySign(uint8_t *signature, uint8_t *pubKey,
13                            uint16_t *digest);
14
15 /* Symmetric session key encryption/decryption. */
16 uint8_t fos_xtea_encipher(uint8_t *msg, uint8_t *key,
17                           uint8_t *cipher, uint8_t nRounds);
18 uint8_t fos_xtea_decipher(uint8_t *cipher, uint8_t *key,
19                           uint8_t *msg, uint8_t nRounds);
20
21 /* Symmetric session key retrieve and store*/
22 fos_xtea_getkey(uint8_t *key, uint8_t location);
23 fos_xtea_storekey(uint8_t *key, uint8_t location);
```

Evaluation (1)

Table I. Comparison of RSA Encryption Times

Public Exponent (e)	Software 1024 bits	Software 2048 bits	Hardware 2048 bits
3	0.45 s	65 s	N/A
65,537	4.185 s	450 s	0.055 s

Table II. RSA Computation Time in TrustedFleck for e 65,537 and 2048 Bit Key

Encryption	Decryption	Sign	Verification
55 ms	750 ms	787 ms	59 ms

Evaluation (2)

Table 4. secFleck (RSA and XTEA) encryption energy consumption for *one bit* of data.

Platform	**Current (mA)**	**Time (μs)**	**Energy (μJ)**
RSA (software, $e = 65,537$, 2048 bit key)	8.0	219,730	7,030.0
RSA (hardware, $e = 65,537$, 2048 bit key)	50.4	27	5.4
XTEA (software, 128 bit key)	8.0	18	0.6

[1] W. Hu, H. Tan, P. Corke, W. C. Shih, and S. Jha, "Towards trusted wireless sensor networks," *ACM Trans. Sensor Networks*, vol. 7, no. 1, pp. 1–25, 2010.

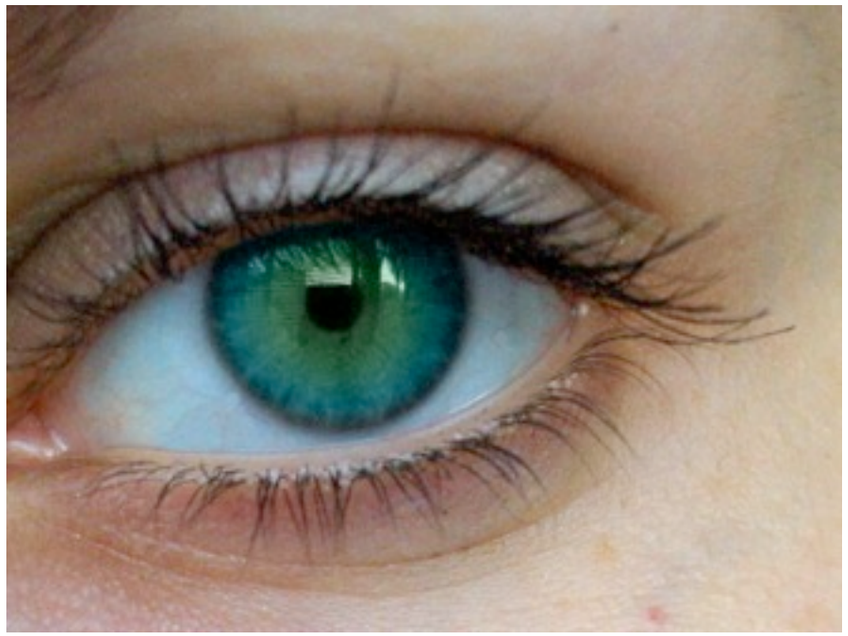
[2] W. Hu, P. Corke, W. C. Shih, and L. Overs, "secFleck: A public key technology platform for wireless sensor networks," in *Wireless Sensor Networks, 6th European Conference (EWSN)*, pp. 296–311, 2009.

More challenges

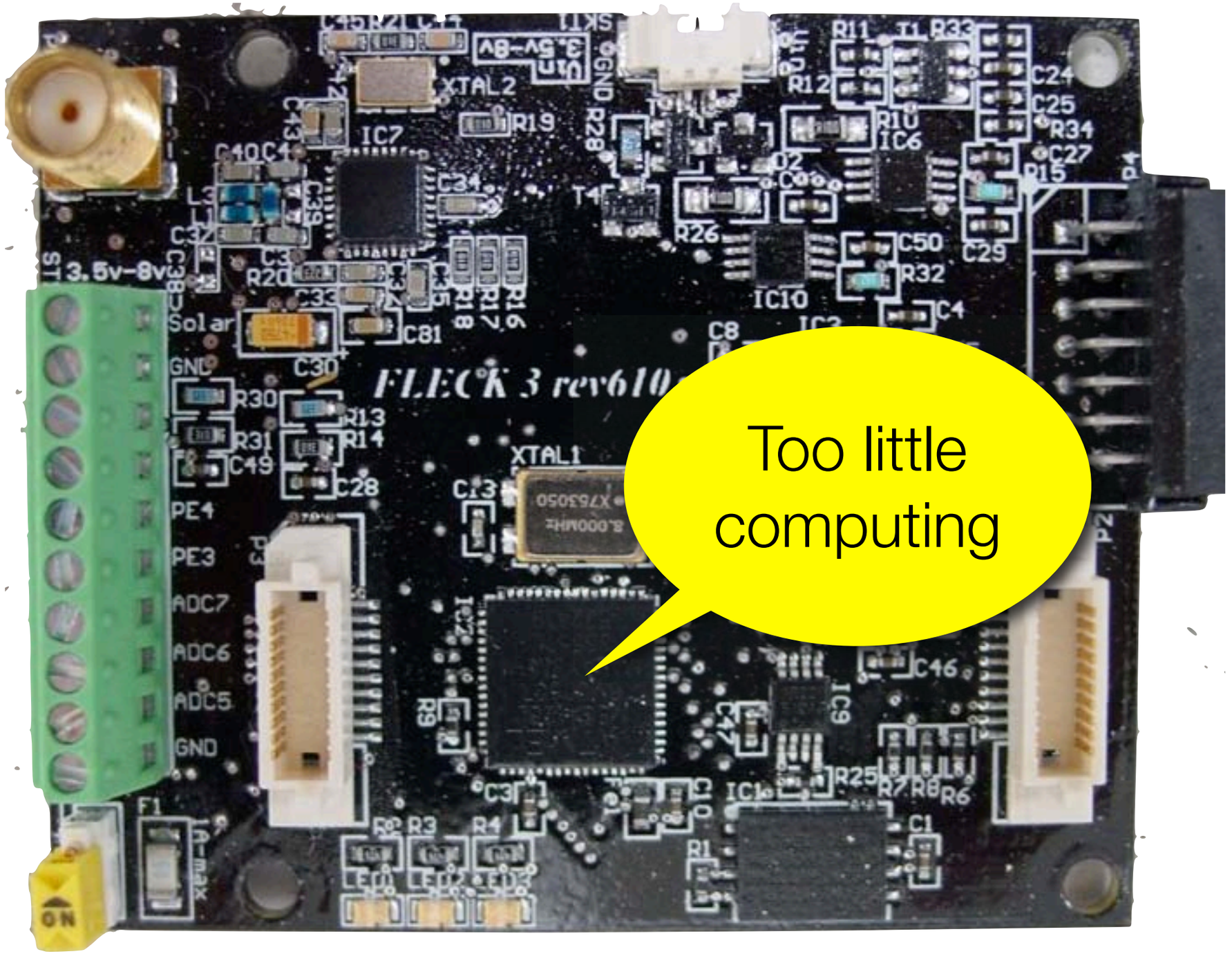
- What about jamming?
  - What about attacks on routing tables?
  - Is end-to-end security enough?

Complex signals

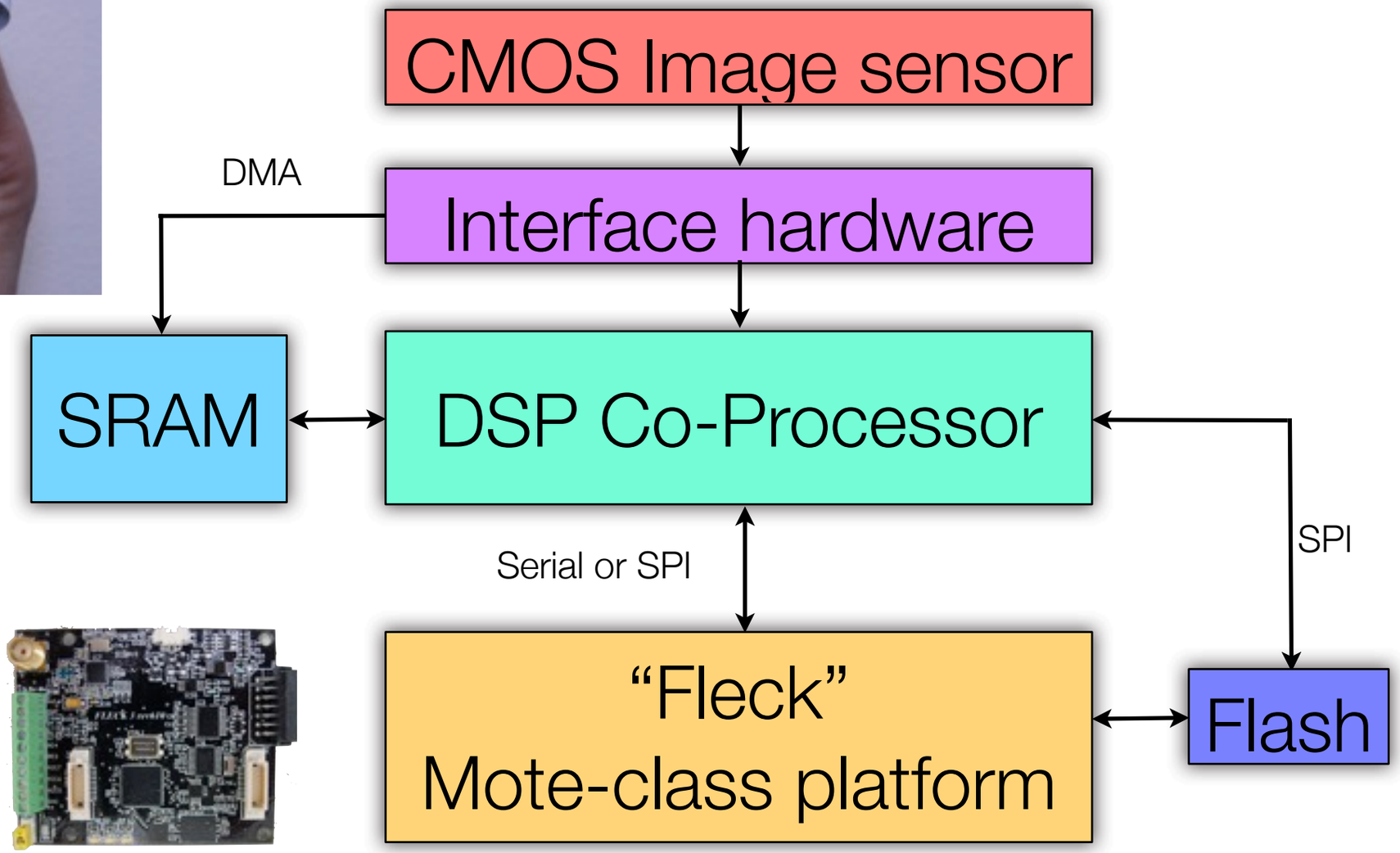
- Humans mostly understanding the world by
  - looking
  - listening




50
9
8
7
6
5


Too little
computing
FLECK 3 rev610
3.5v-8v
Solar
GND
PE4
PE3
ADC7
ADC6
ADC5
GND
XTAL1
XTAL2
ON

Multi-media hardware architecture



AD Blackfin DSP / Camera Board

- Blackfin DSP (ADSP-BF537)
  - AD 32 bit, 600 MHz processor
  - 132KB SRAM + 32MB external SD RAM
  - 4MB flash
  - 16bit external memory bus
  - No MMU
  - Runs uClinux or AD Visual DSP++
- Programming
  - JTAG or ethernet interface for programming
- Fleck interface
  - Serial
  - (Currently implementing SPI interface - with Fleck as SPI master)

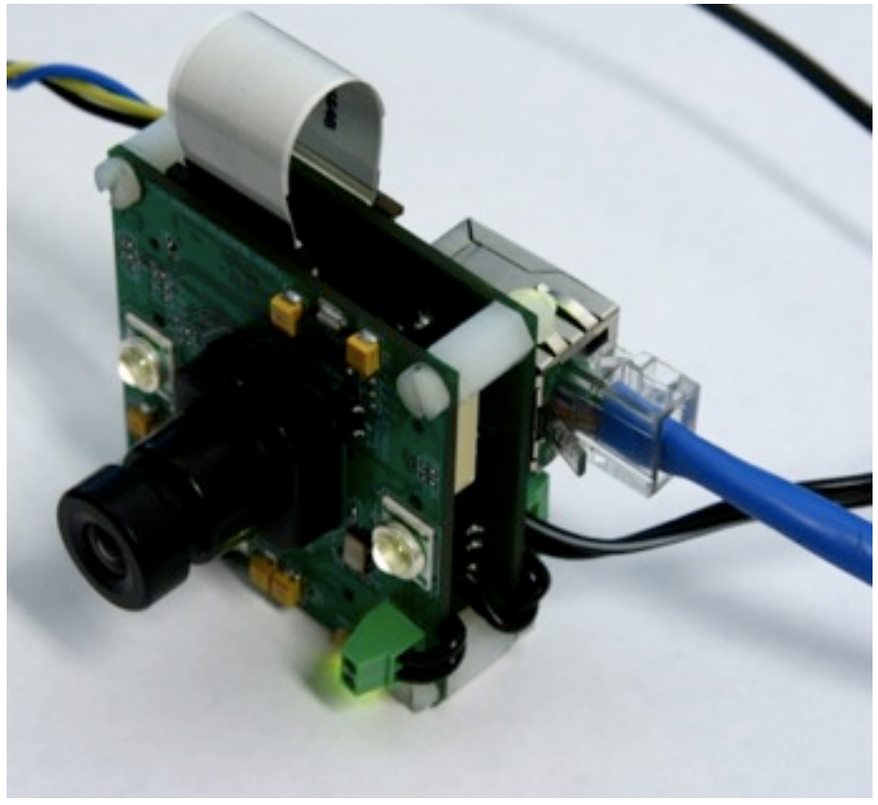


Image Transfer - Energy Comparison (TI)

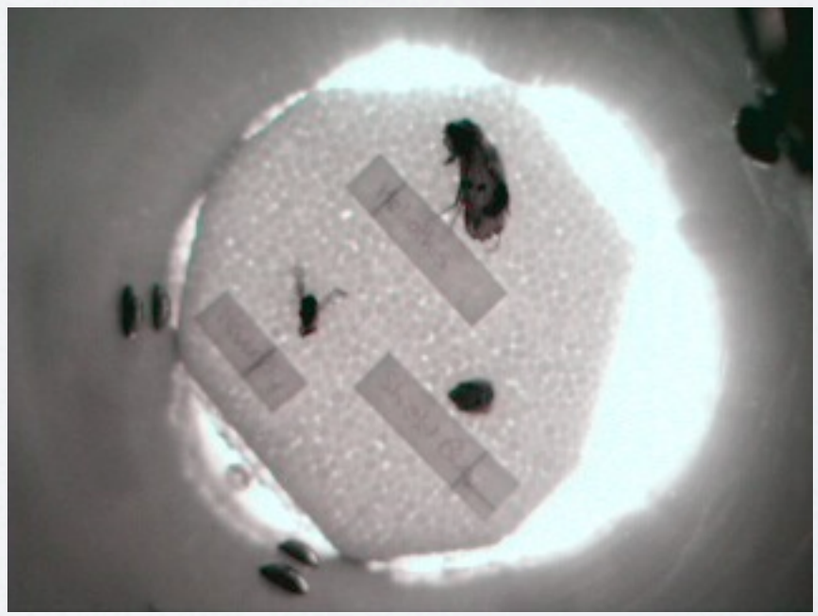
	Camera On	DSP on	DSP → MMC	MMC → TX
Voltage	3.3V	3.3V	3.3V	3.3V
Current	30mA	240mA	270mA	50mA
Power	99mW	792mW	891mW	165mW
Time	0.03s	0.1s	1.5s	40s
Energy	3.0mJ	79.2mJ	1336mJ	6600mJ

8018mJ

	Camera On	DSP on	DSP → TX
Voltage	3.3V	3.3V	3.3V
Current	30mA	240mA	260mA
Power	99mW	792mW	858mW
Time	0.03s	0.5s	0.8s
Energy	3.0mJ	396mJ	687mJ

1086mJ

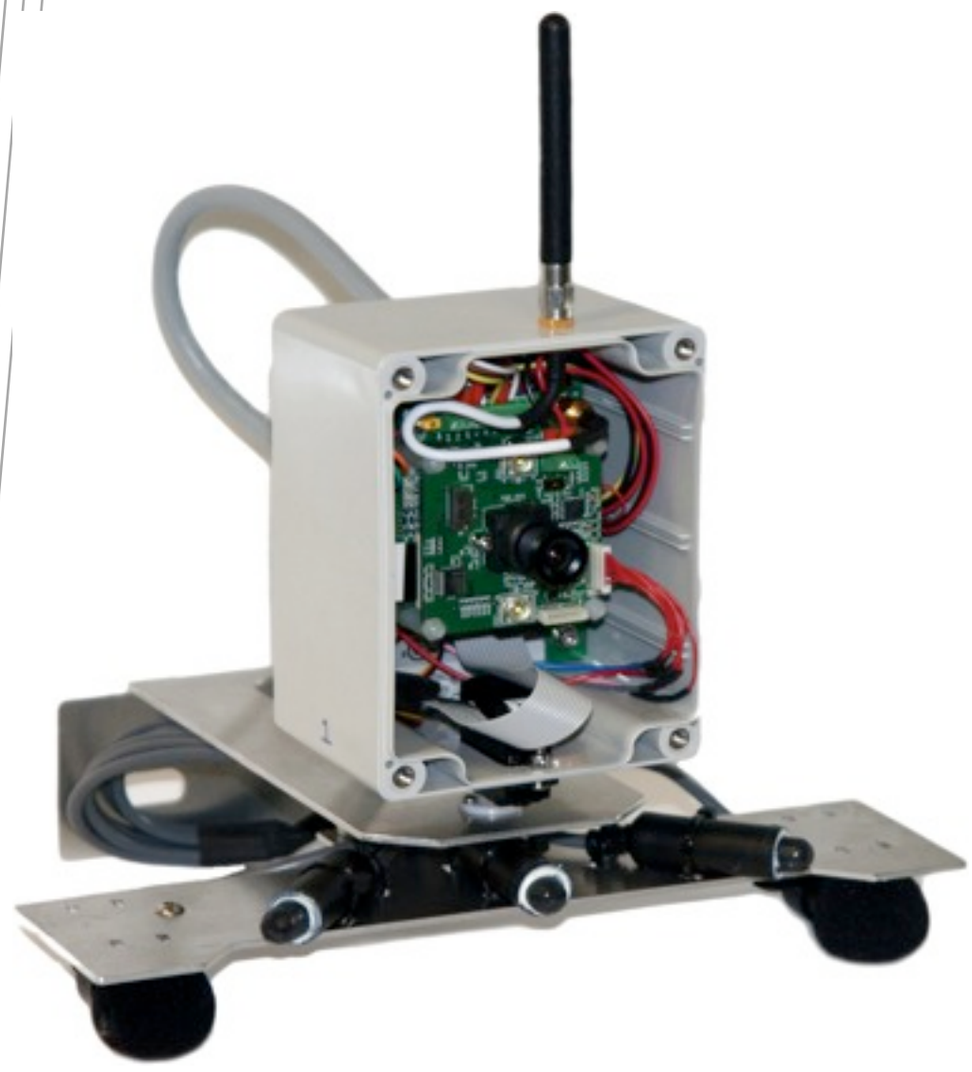
8 x times less energy with compression

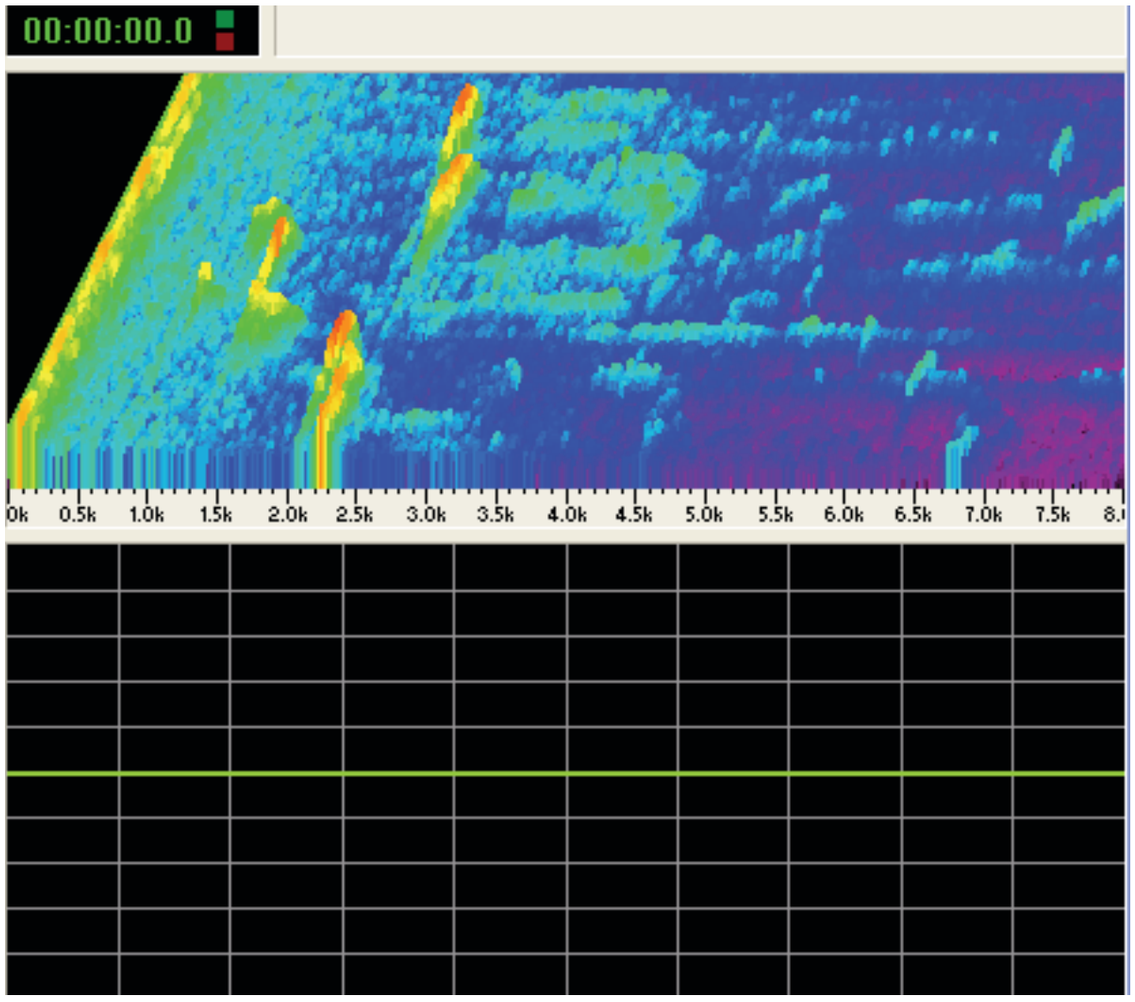


Thursday, 16 February 2012

Audio/Video nodes

- Local-computation class nodes
- Event detection
- Complex signals (e.g. audio or video)





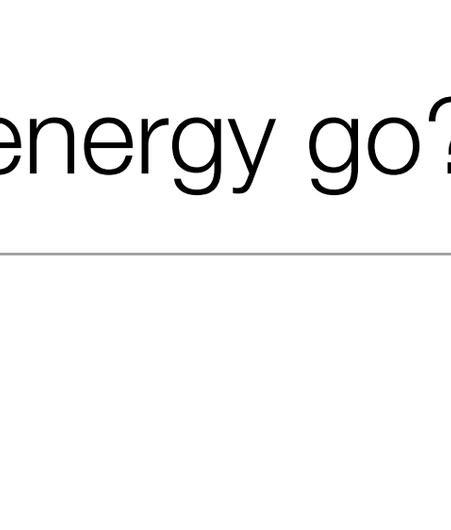
O'Rourke D., Liu J., Wark T., et.al, “Towards a Framework for a Versatile Wireless Multimedia Sensor Network Platform,” ACM/IEEE Information Processing in Sensor Networks (IPSN), 2010.

Hu. W, Bulusa N, Chou C T., et.al, "The Design and Evaluation of a Hybrid Sensor Network for Cane-toad Monitoring", *ACM Transactions on Sensor Networks (TOSN)*, Volume 5, Issue 1 , 2009.

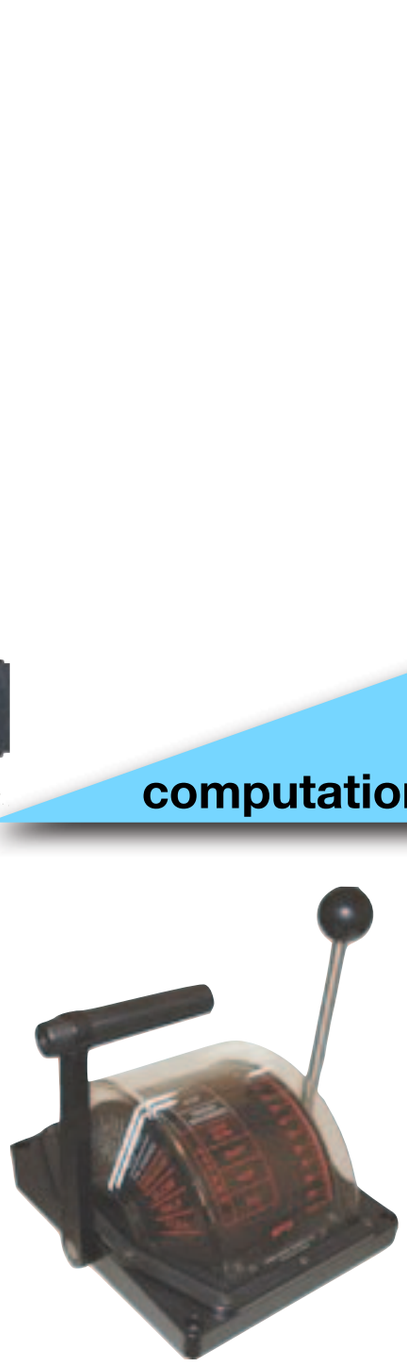
Wark T., Corke P., Liu J. and Moore D., "Design and evaluation of an image analysis platform for low-power, low-bandwidth camera networks", *Proc. ImageSense /ACM Sensys*, 2008.

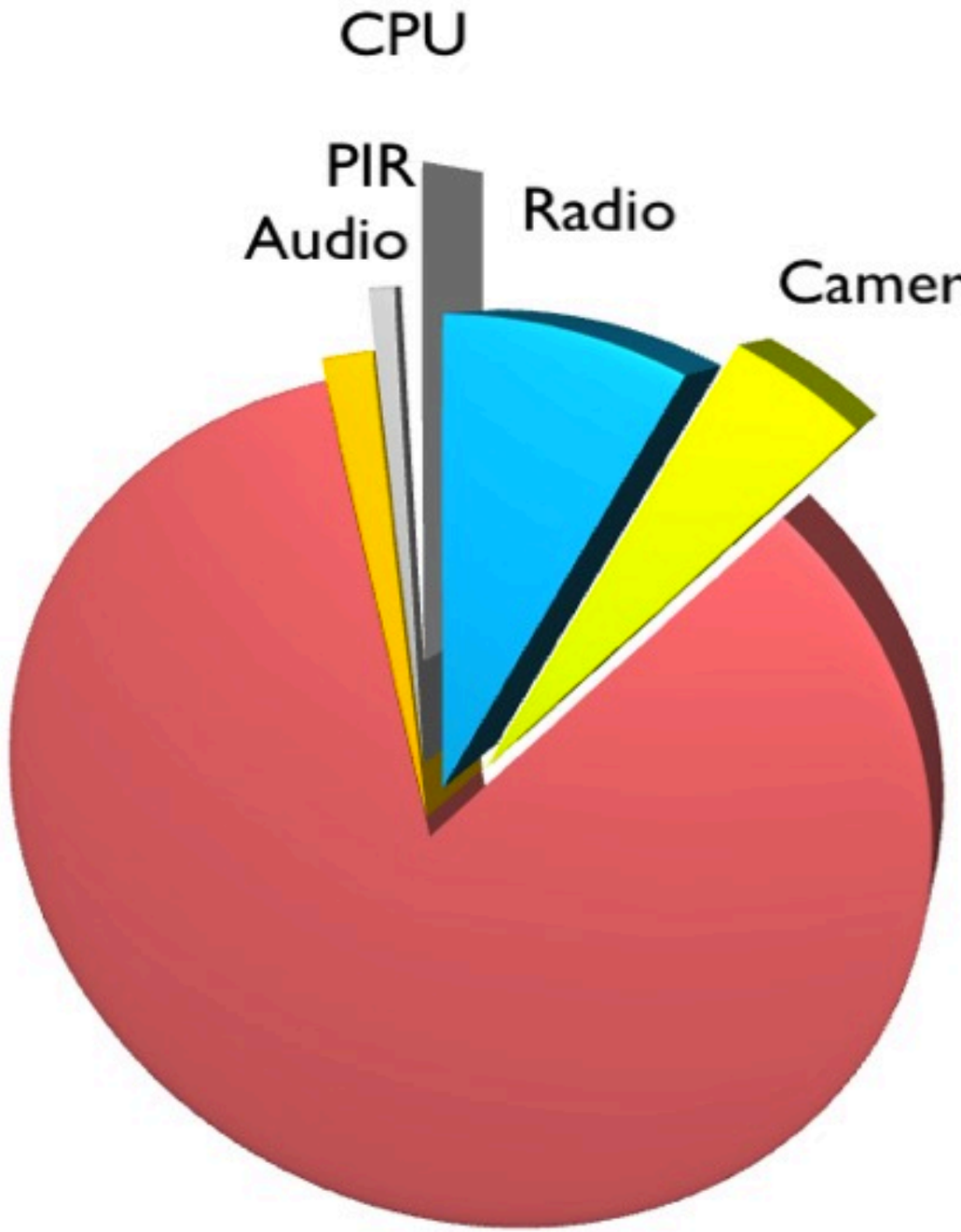
CSIRO

Where does the energy go?

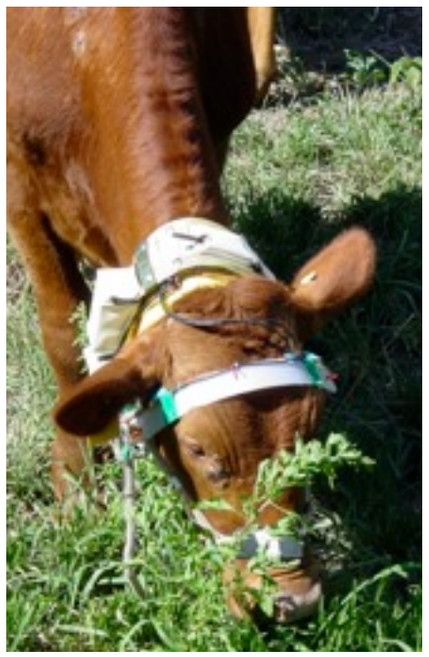


computation



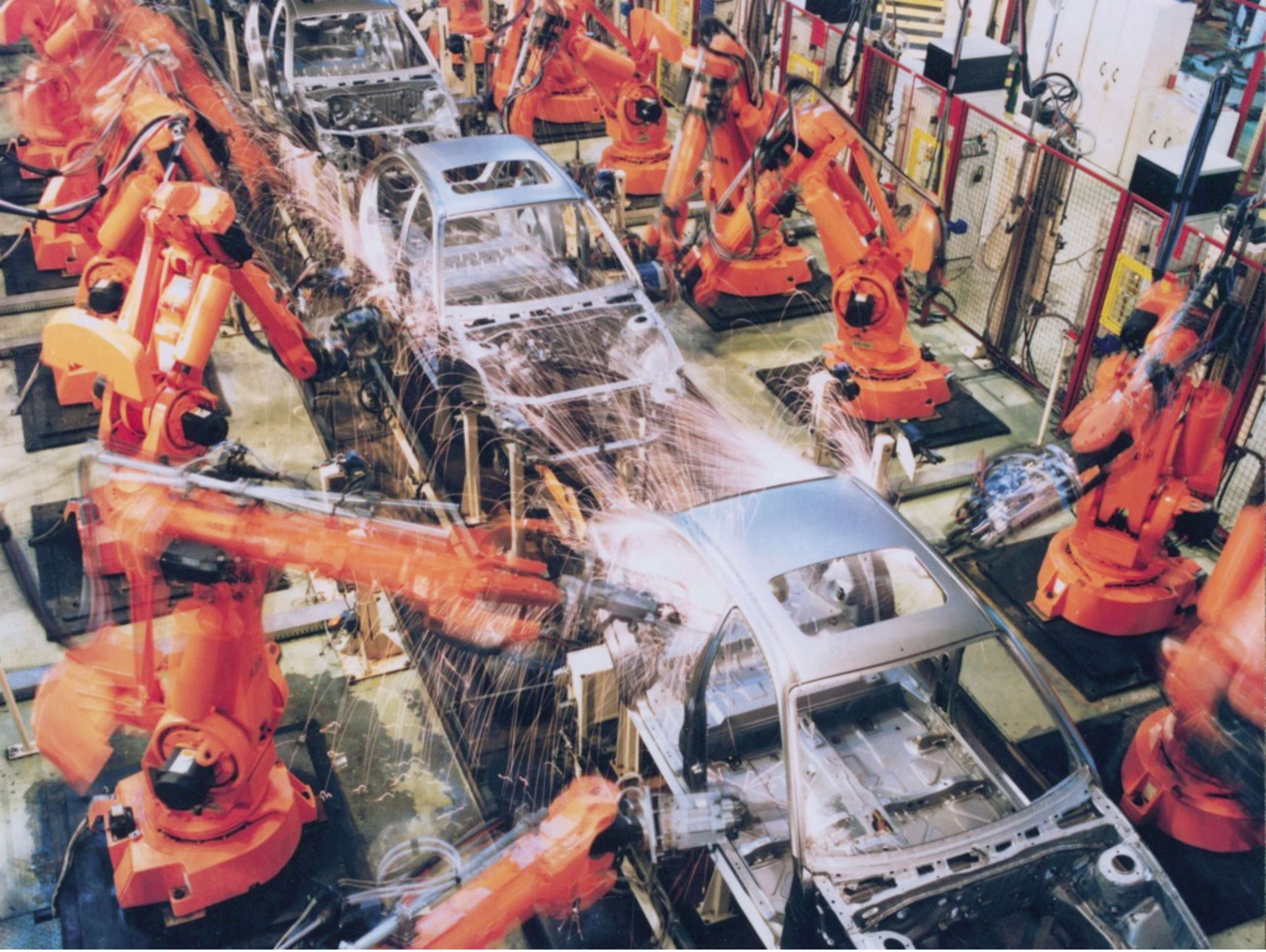


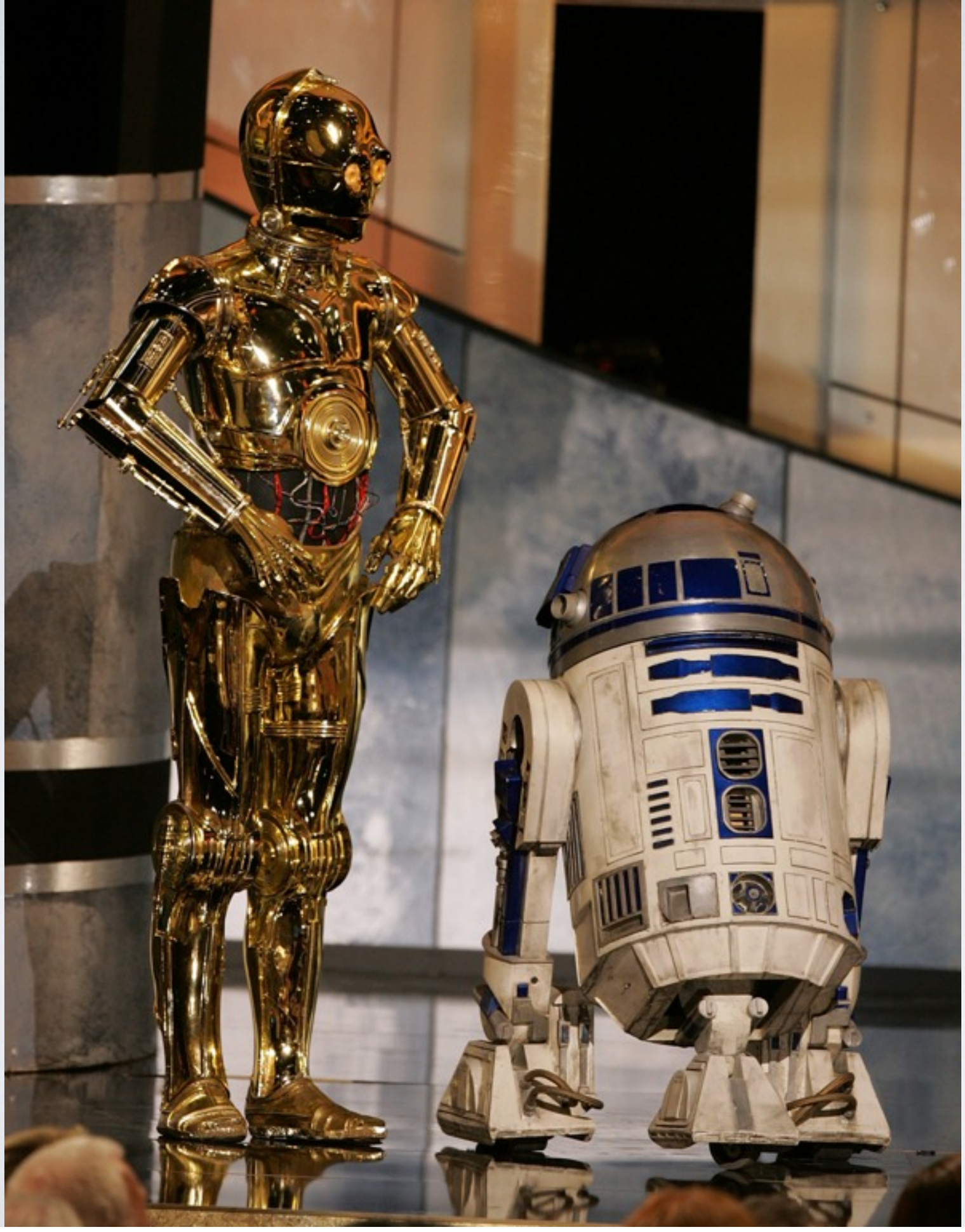


2003	2005-6	2006-7	2007-9	2008-9	2009-9
TOS 1.x	TOS 1.x	TOS1.x	FOS	FOS	FOS
ZTDMA	ZTDMA	MintRoute	Diffusion	LQ/LPL	LQ/LPL
Fleck1C	Fleck2	Fleck3	Fleck3	Fleck3	Fleck3


But what's happening here?
T=24C





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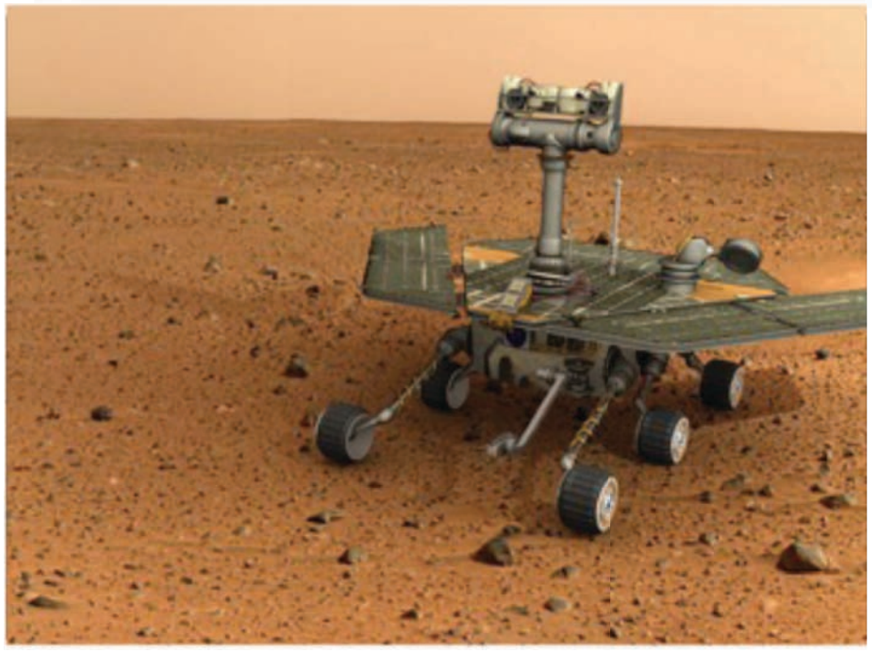

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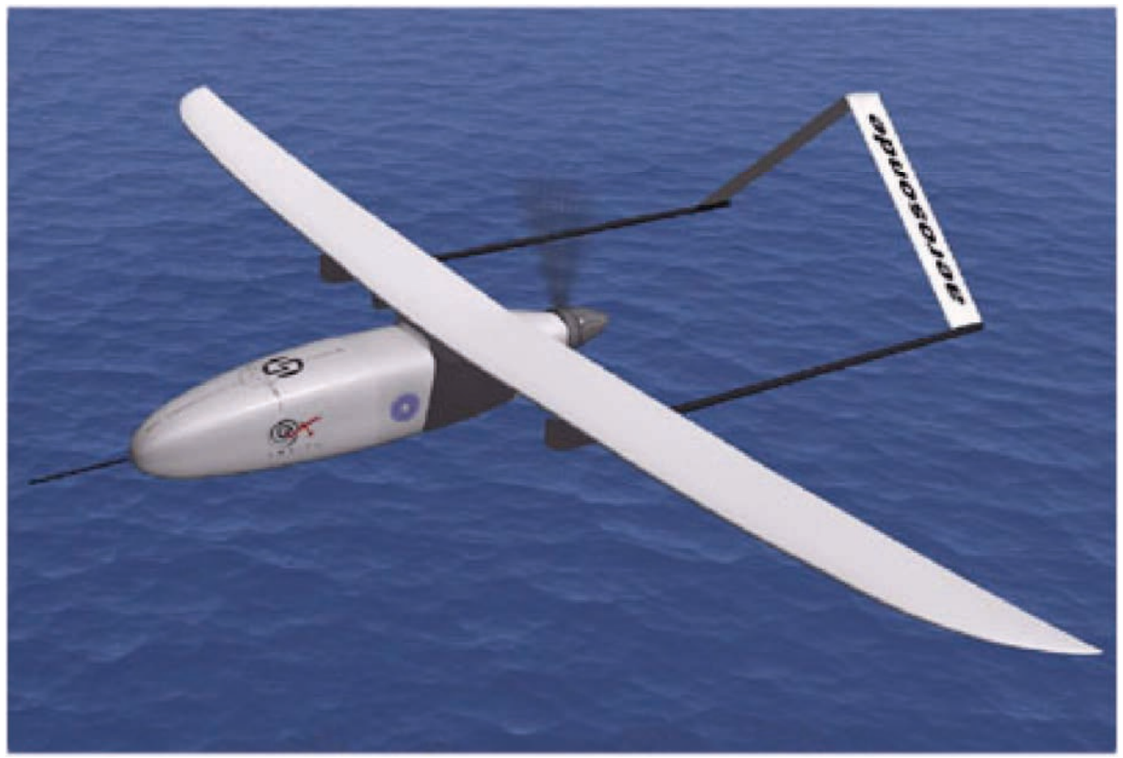
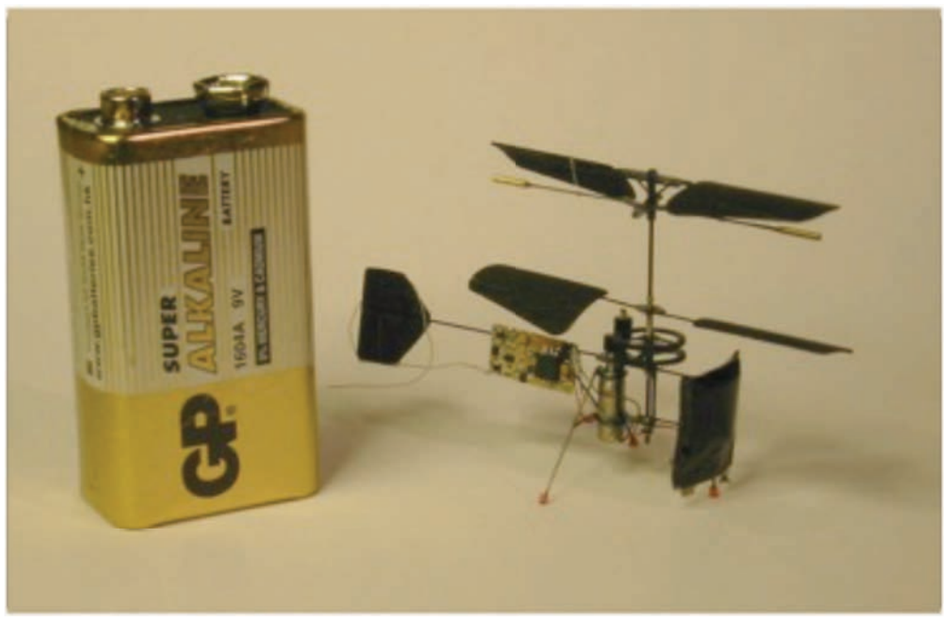
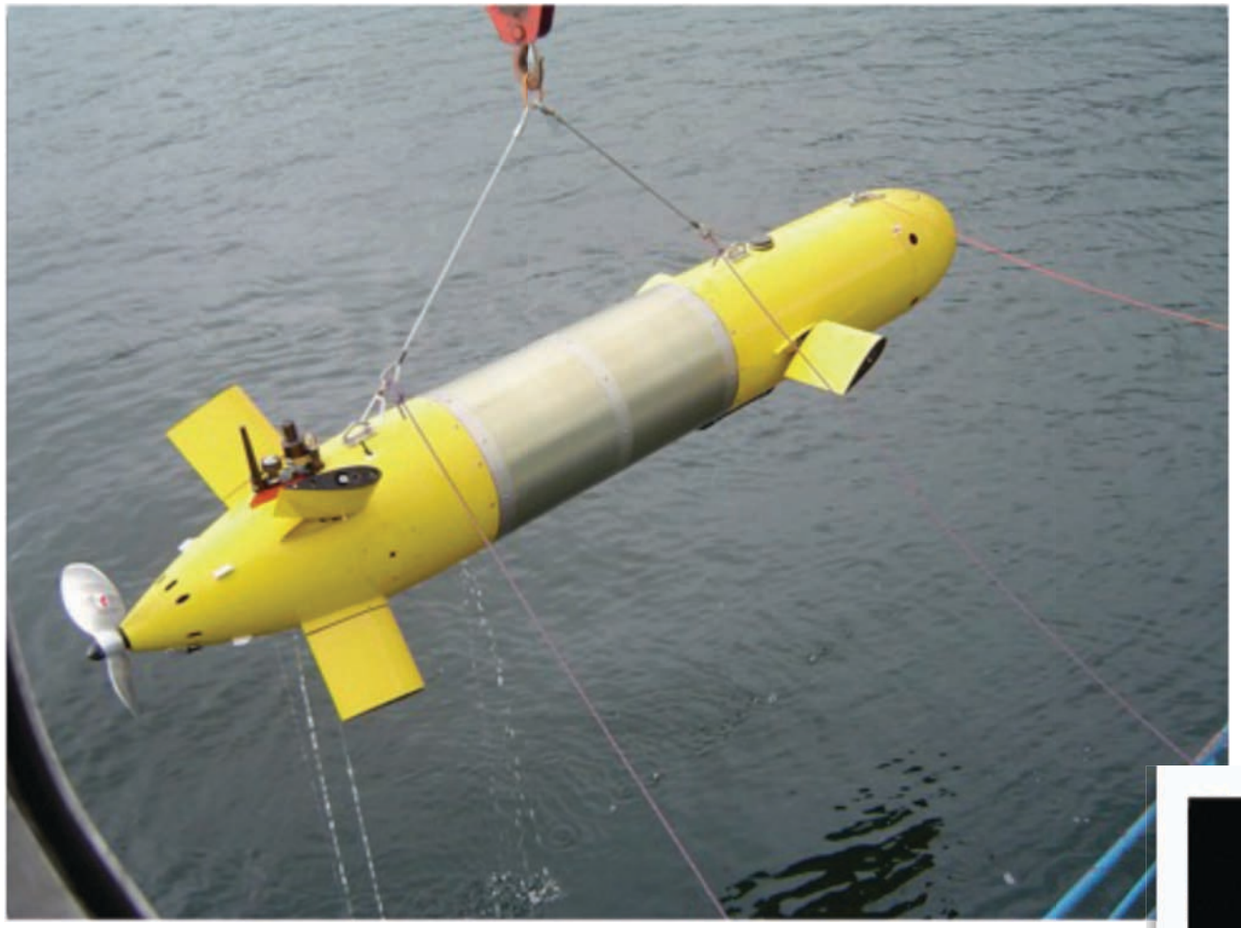
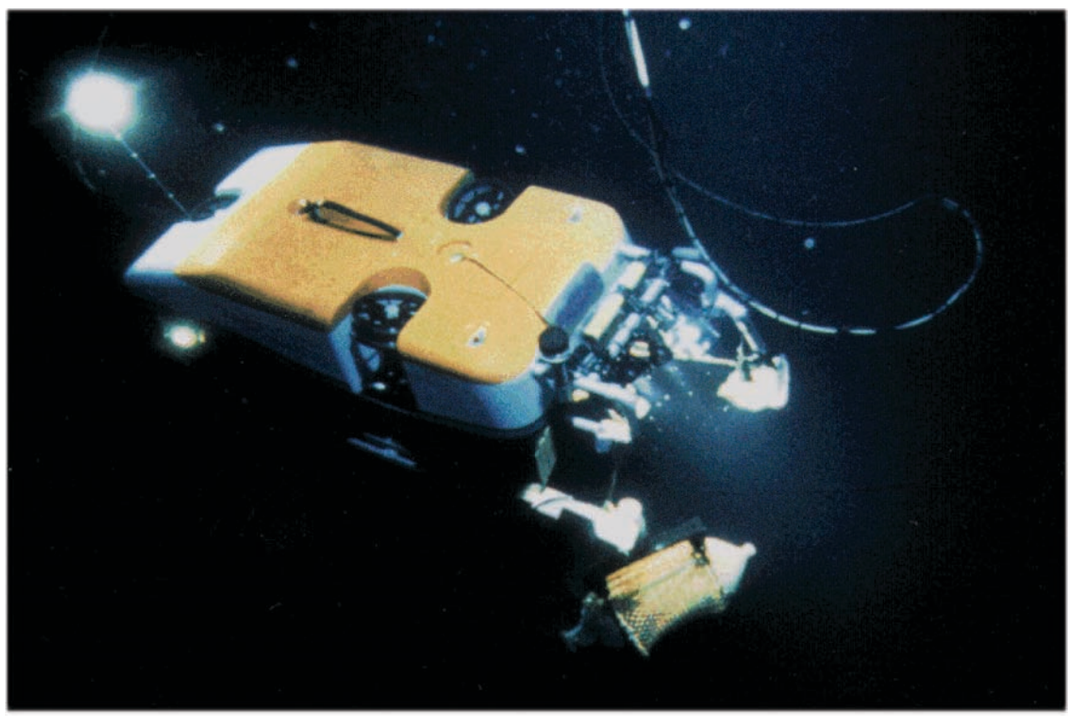
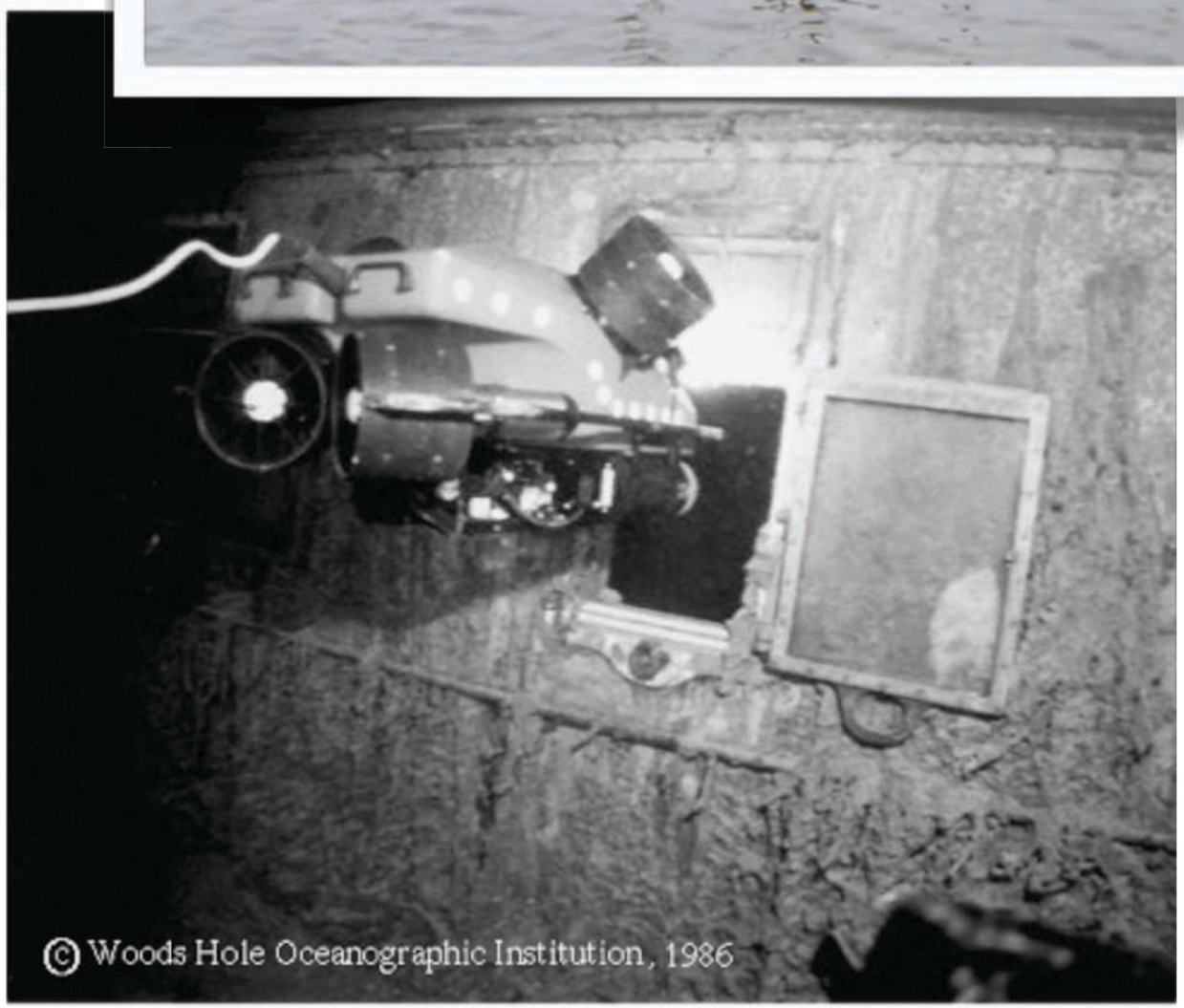

SOLARSTRATOS


SUPER
ALKALINE
GP






© Woods Hole Oceanographic Institution, 1986

Sensor networks and robots are complementary

- **SN**
  - Sense globally (sparse)
  - Static
  - Limited resources
  - Network to transport robot's data
  - Localize a robot
- **Robot**
  - Sense locally
  - Mobile
  - Abundant resources
  - Physical transport of SN's data
  - Localize nodes
  - Deploy nodes

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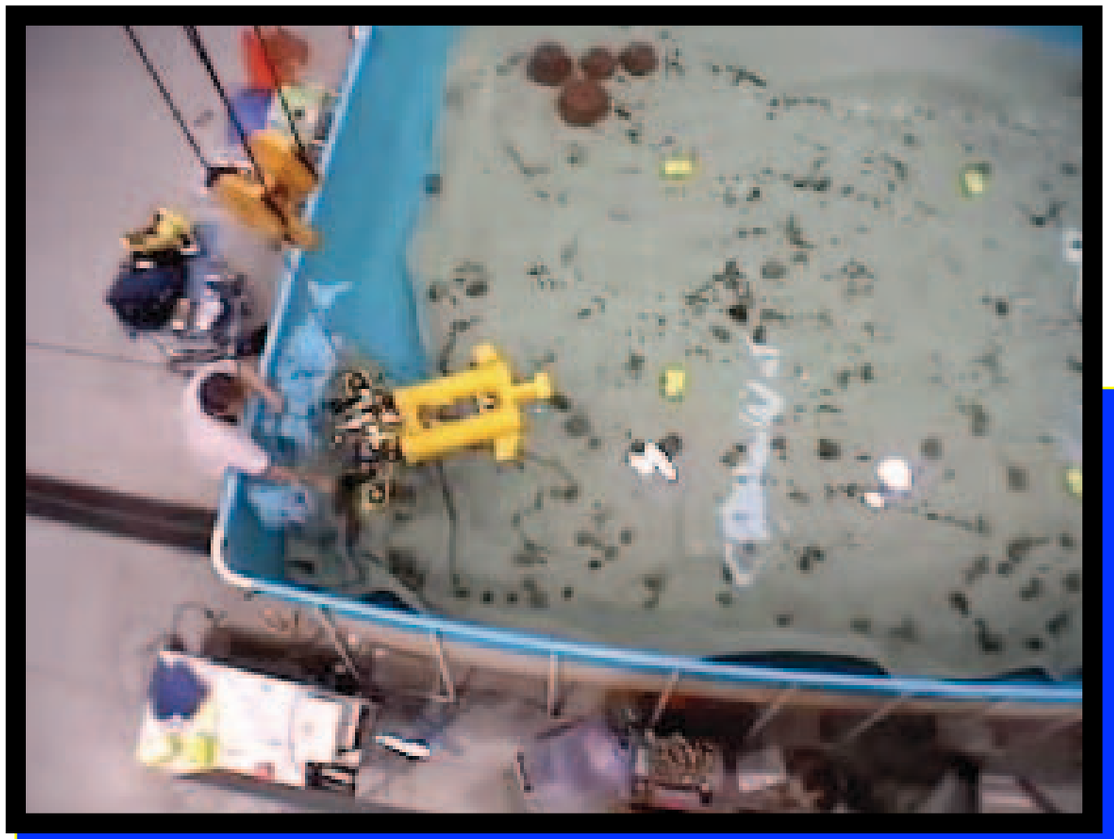
Robotic deployment

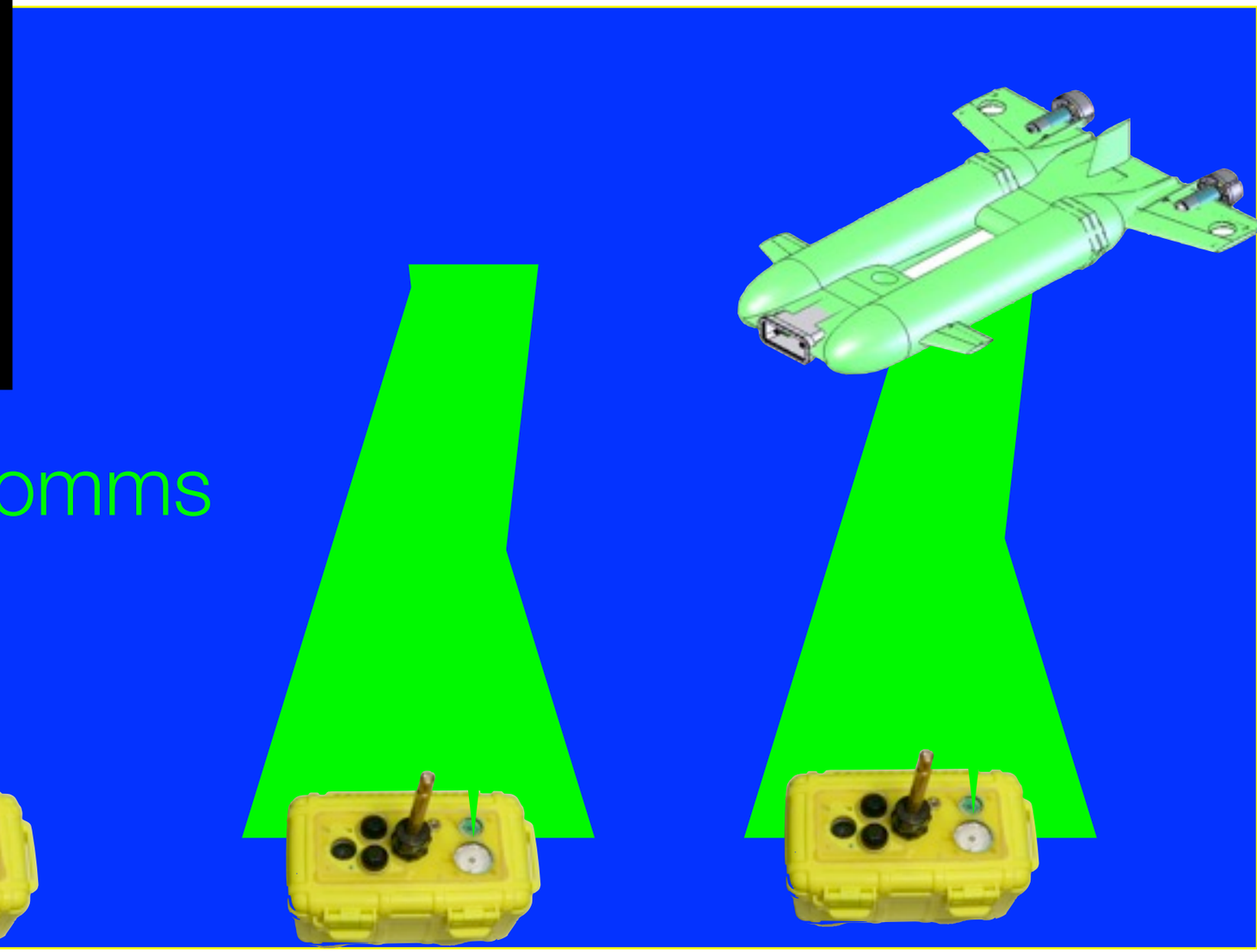
with USC and MIT

2003

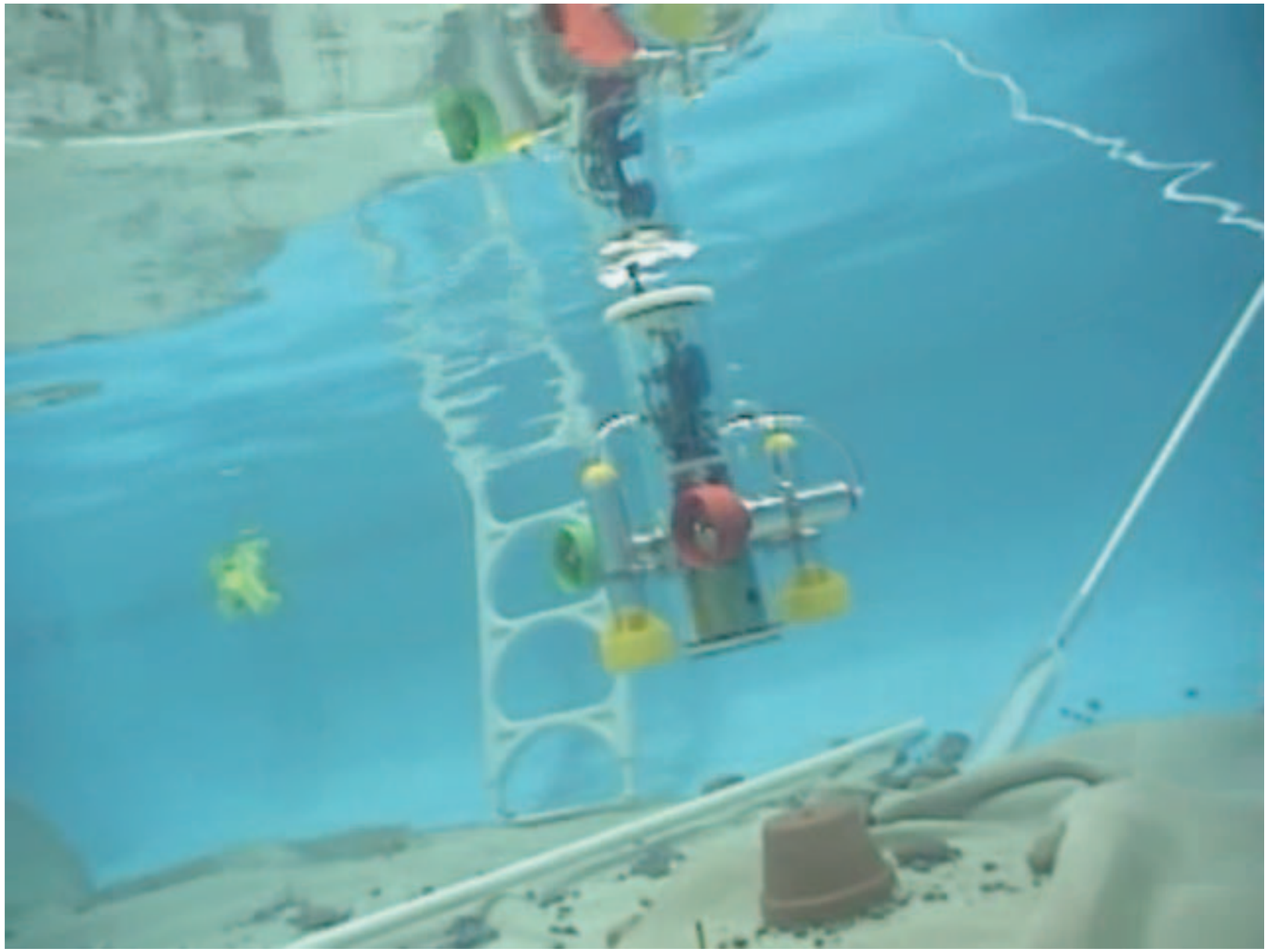
Robotic data muling



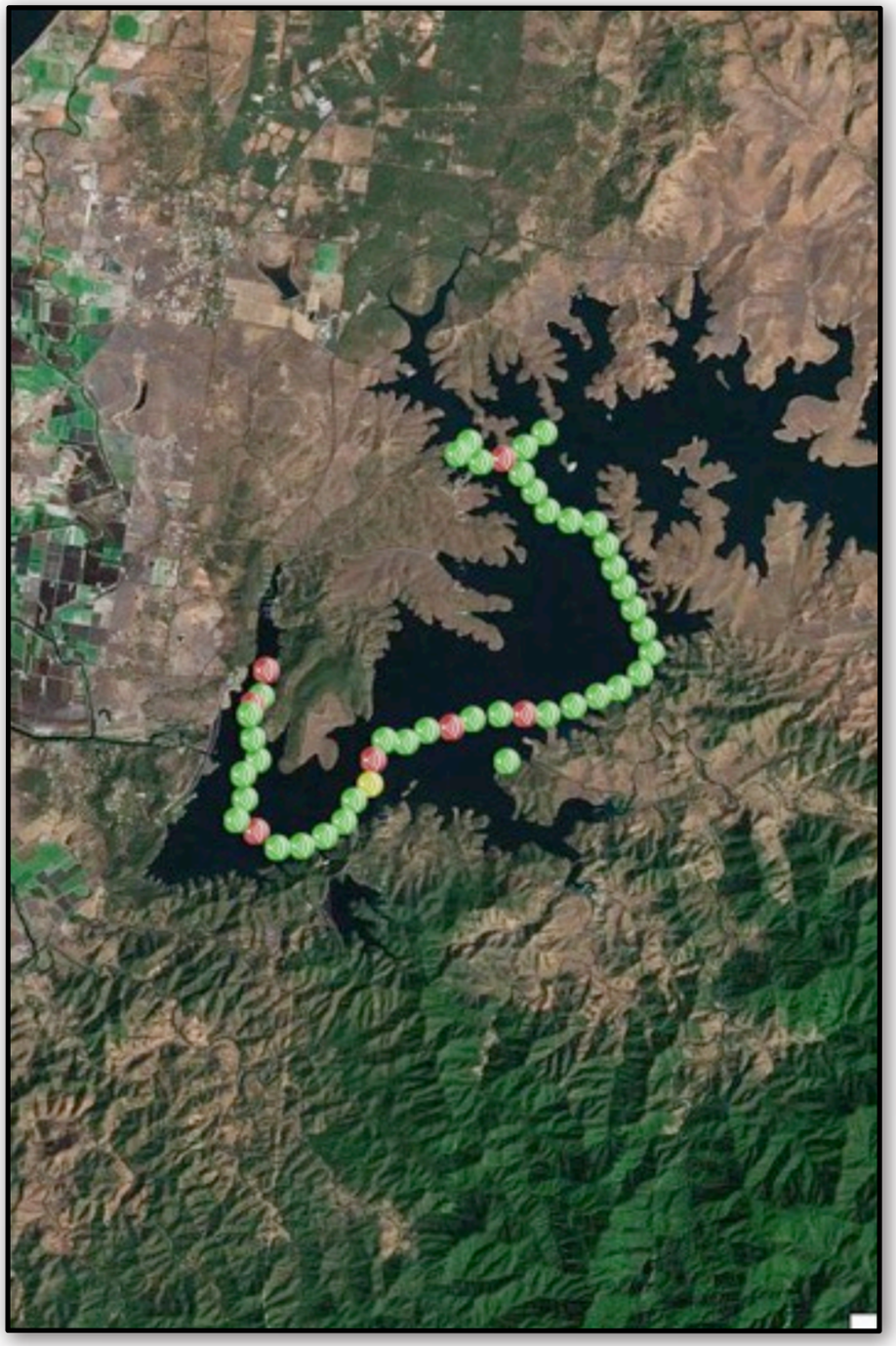
CSIRO-MIT experiments
2005



Robotic node pickup



Application: Lake Monitoring



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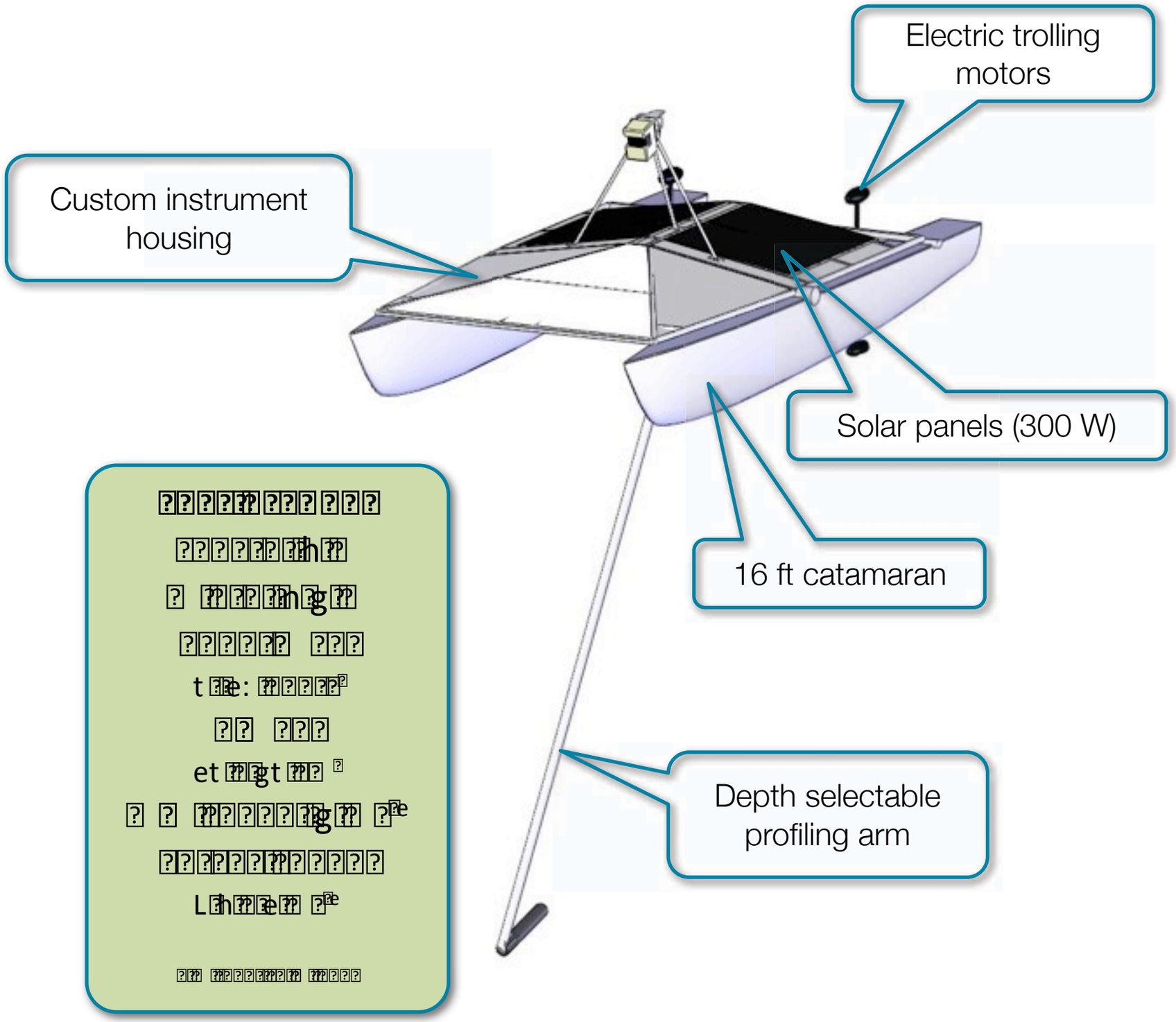
ASV Nikki



Navigational sensors

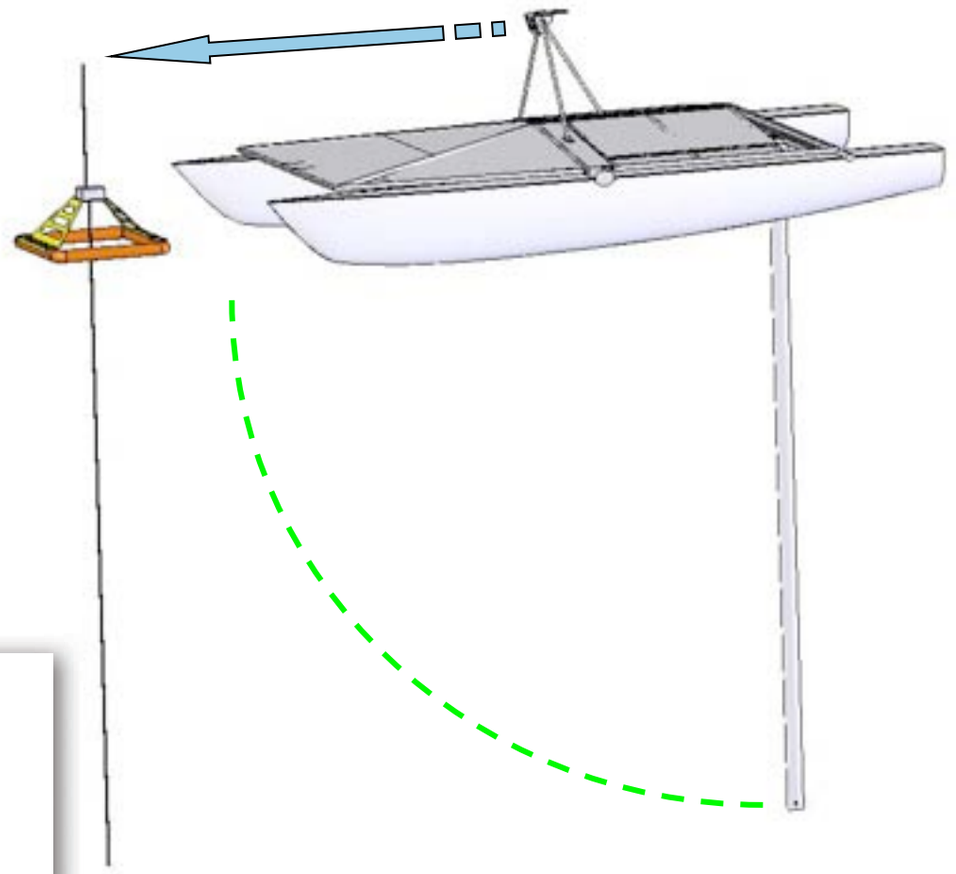
- Laser scanner
- GPS / compass
- Camera
- Depth sounder
- Wind speed

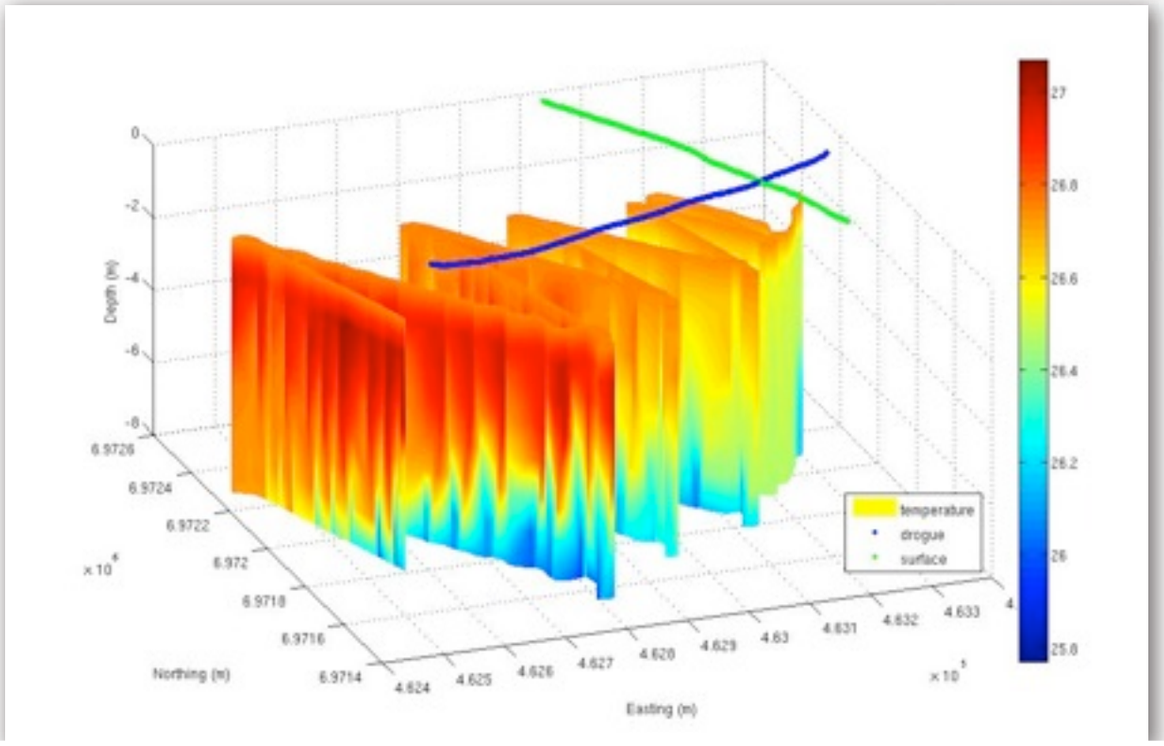
Environmental sensors

- Optical Methane Detector
- YSI Sonde
- Rhodamine Fluorometer
- Odyssey light logger
- Tritech Profiling Sonar

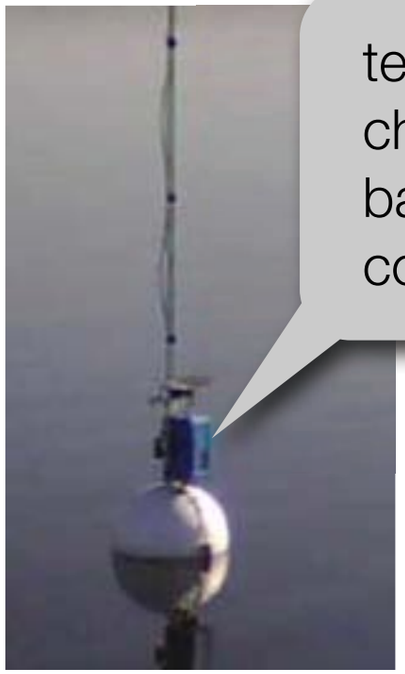
Calibration and mobile sensing

- In-situ node temperature calibration
  - Offset determination
  - Relay information to node
- Node inspection
  - Localization
  - Condition assessment
- 3d temperature profiling

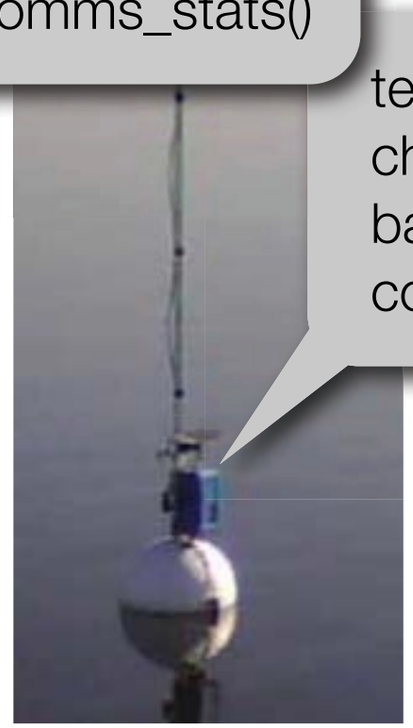




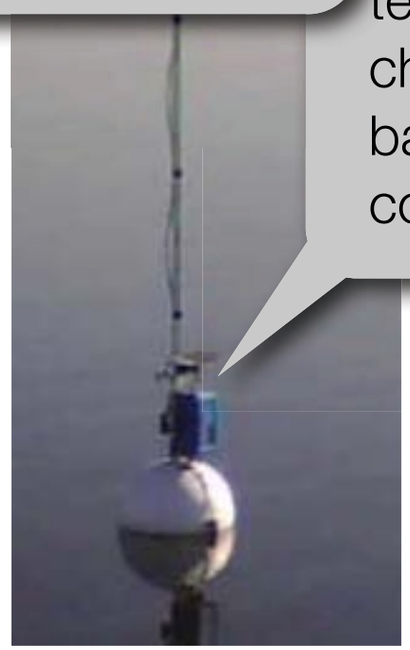
Abstraction: Service-based sensor network



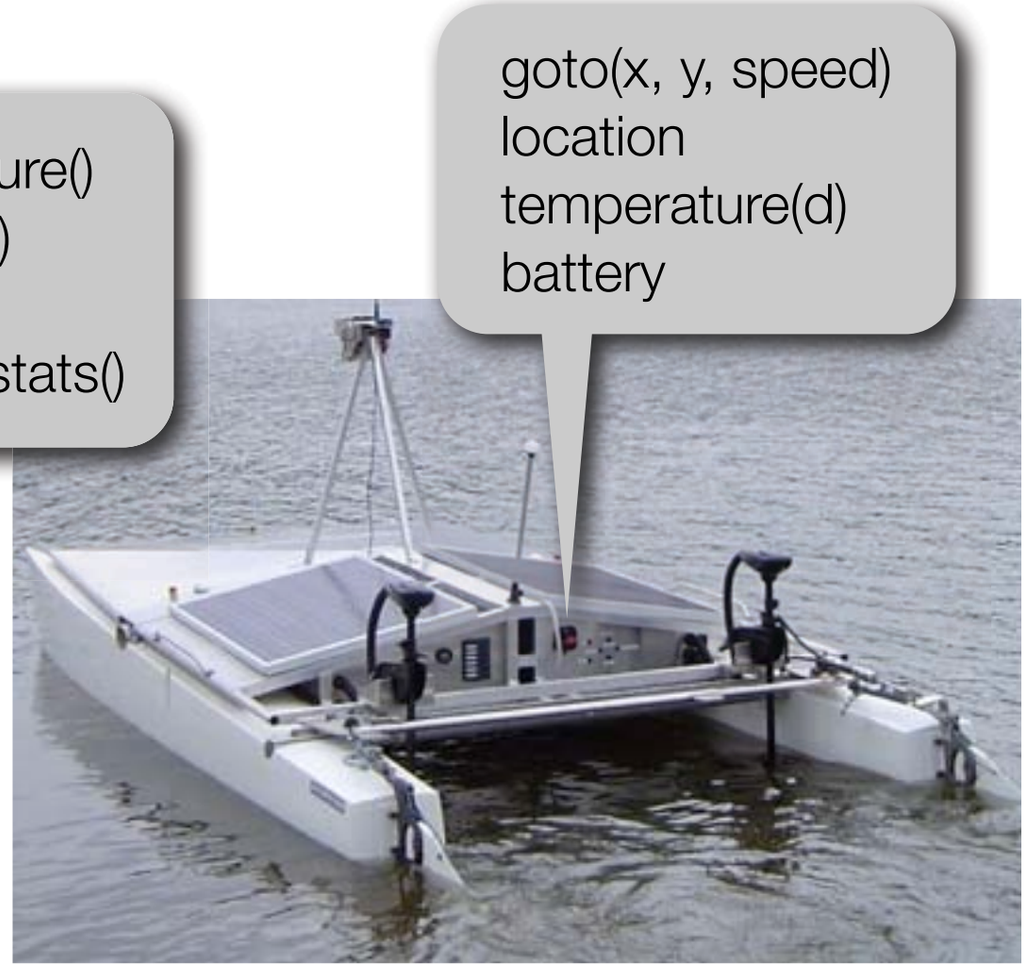
temperature()
charging()
battery()
comms_stats()



temperature()
charging()
battery()
comms_stats()



temperature()
charging()
battery()
comms_stats()

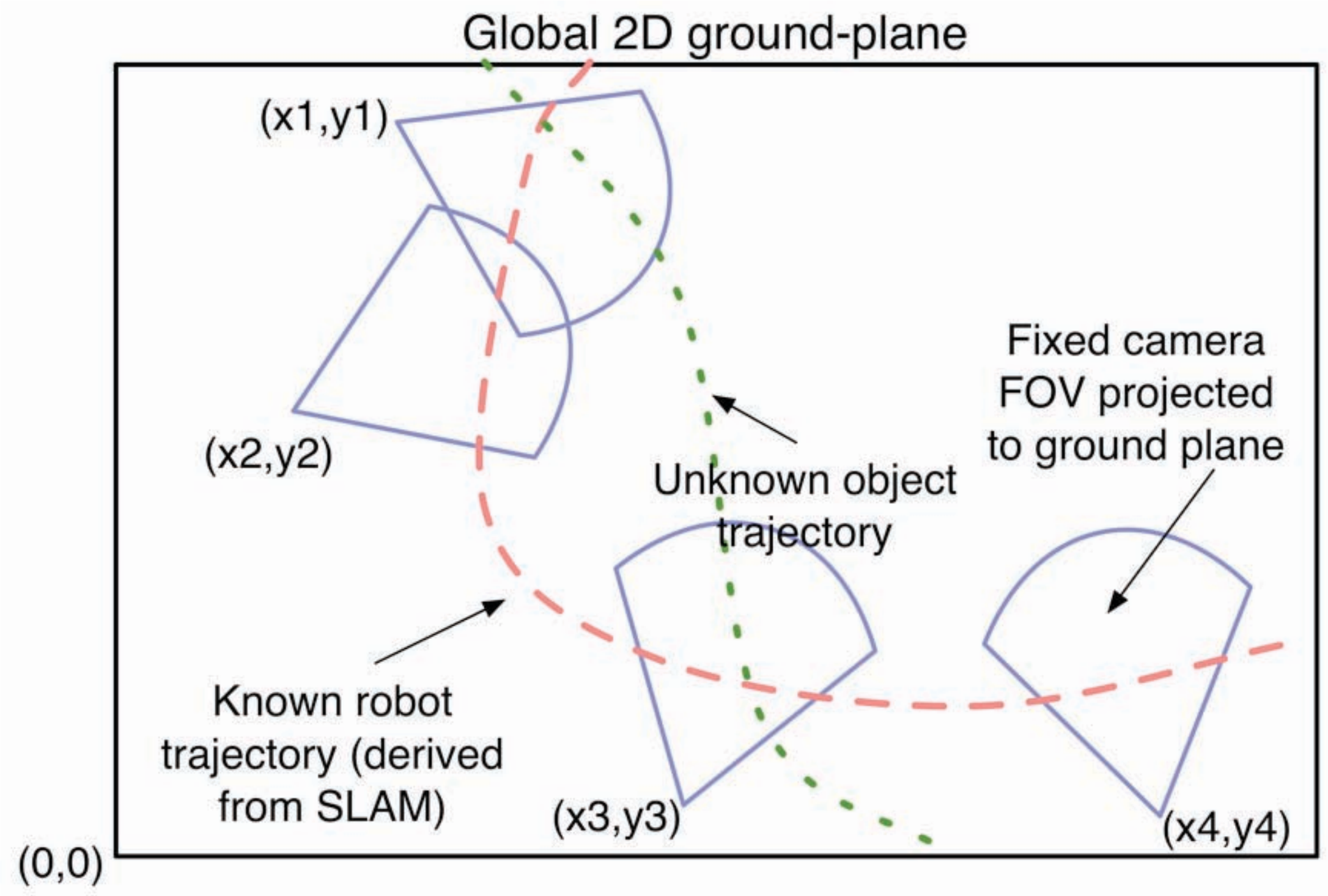


goto(x, y, speed)
location
temperature(d)
battery

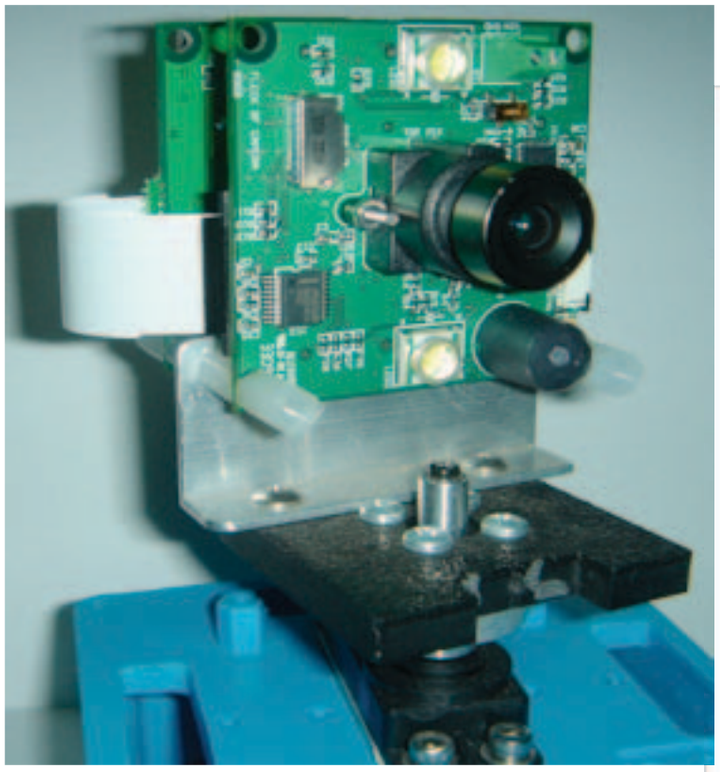
Learnings

- Radio propagation is poor over water (~ 150m)
- RPCs make life easy
- Physical robustness important

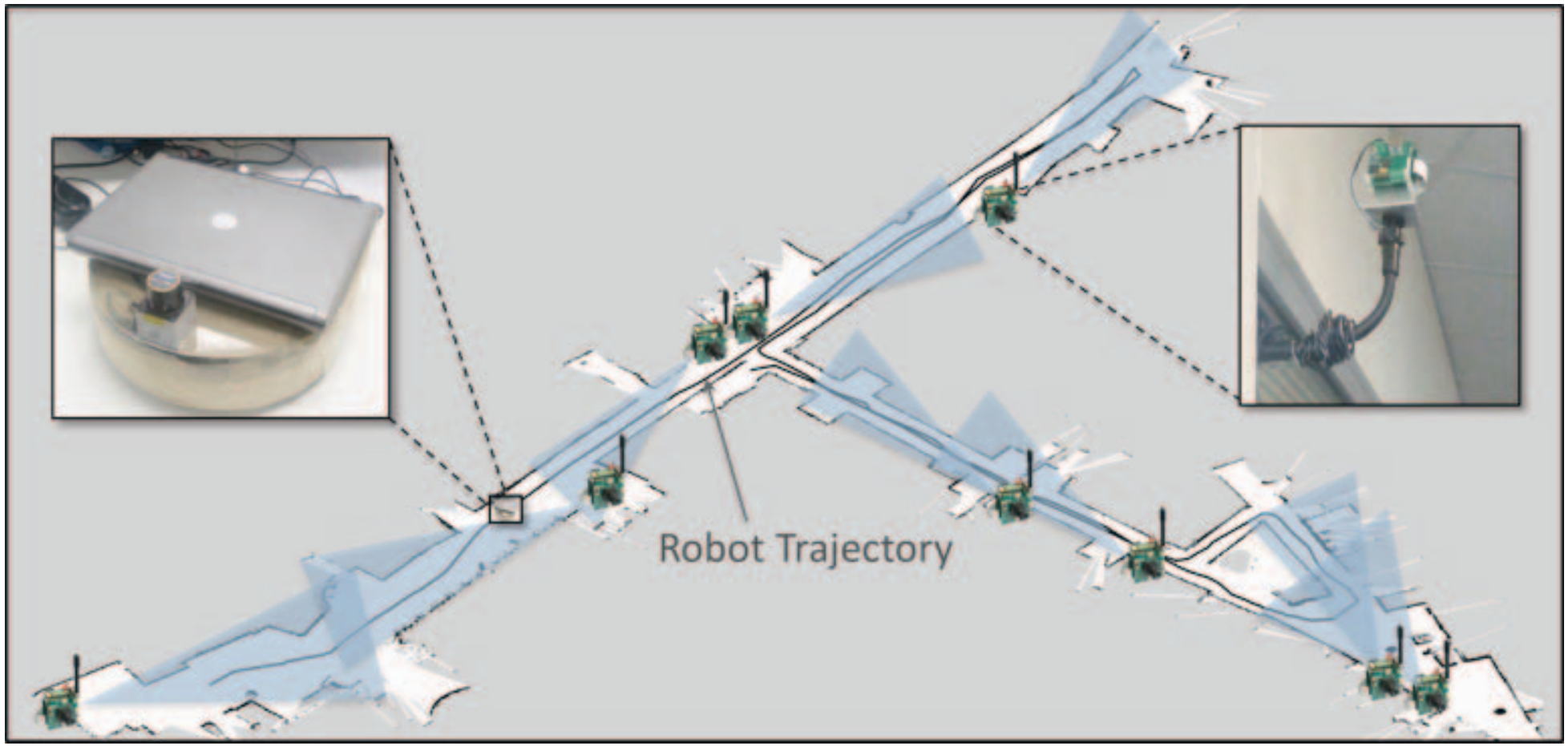
Camera-based surveillance



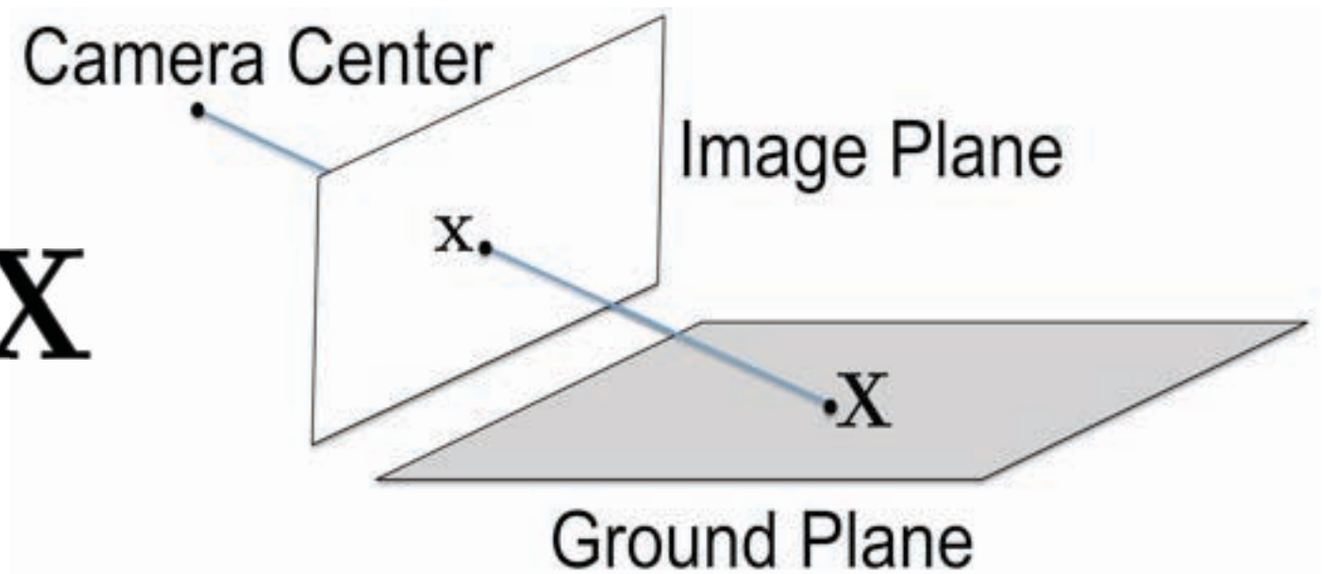
Object tracking



Where are the cameras?



$$\mathbf{x} = \mathbf{H}\mathbf{X}$$

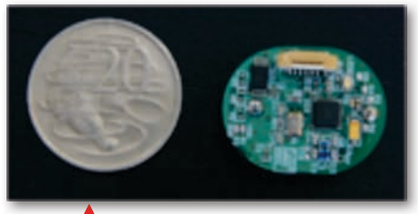


History of the CSIRO's Fleck™ Hardware

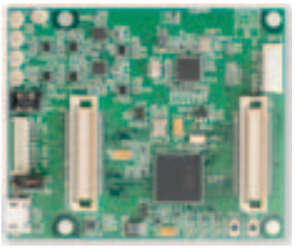
Fleck2

6 on loan from Dartmouth

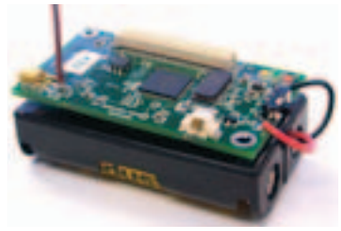
Fleck3

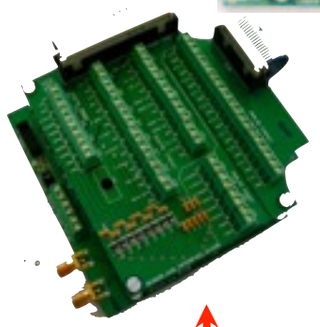


Fleck Nano



Opal





Sensor hub

Licence

Fleck1A
1st proto

Fleck1C

Fleck3B

2003 2004 2005 2006 2007 2008 2009 2010 2011

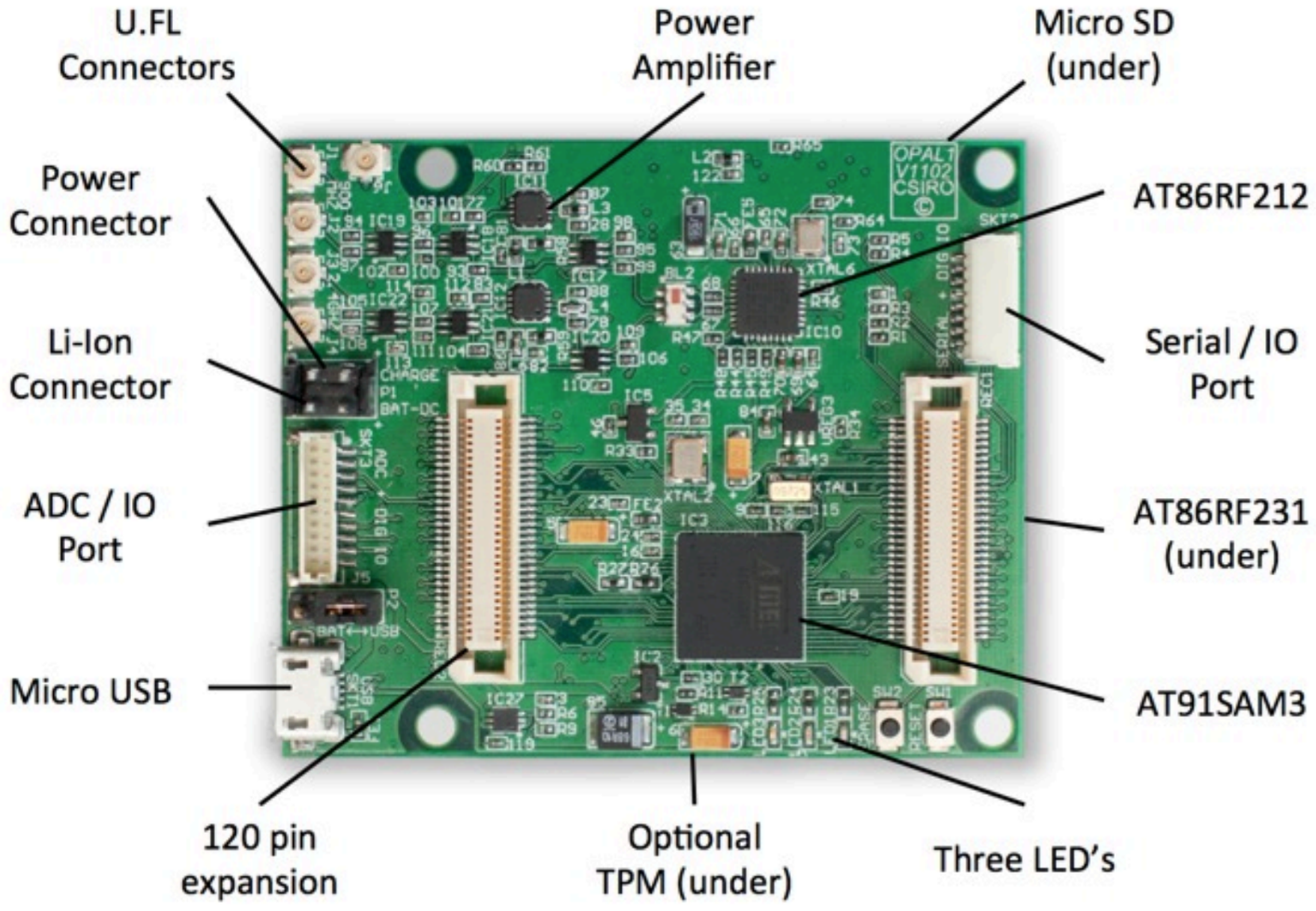
Sensor boards

- Light, Temp
- Water Quality: pH, Redox, Temp, Conductivity
- Soil Moisture
- Motion: GPS, Accel,Gyro, Magnetometer
- Strain Gauges
- DSP: Audio, Video

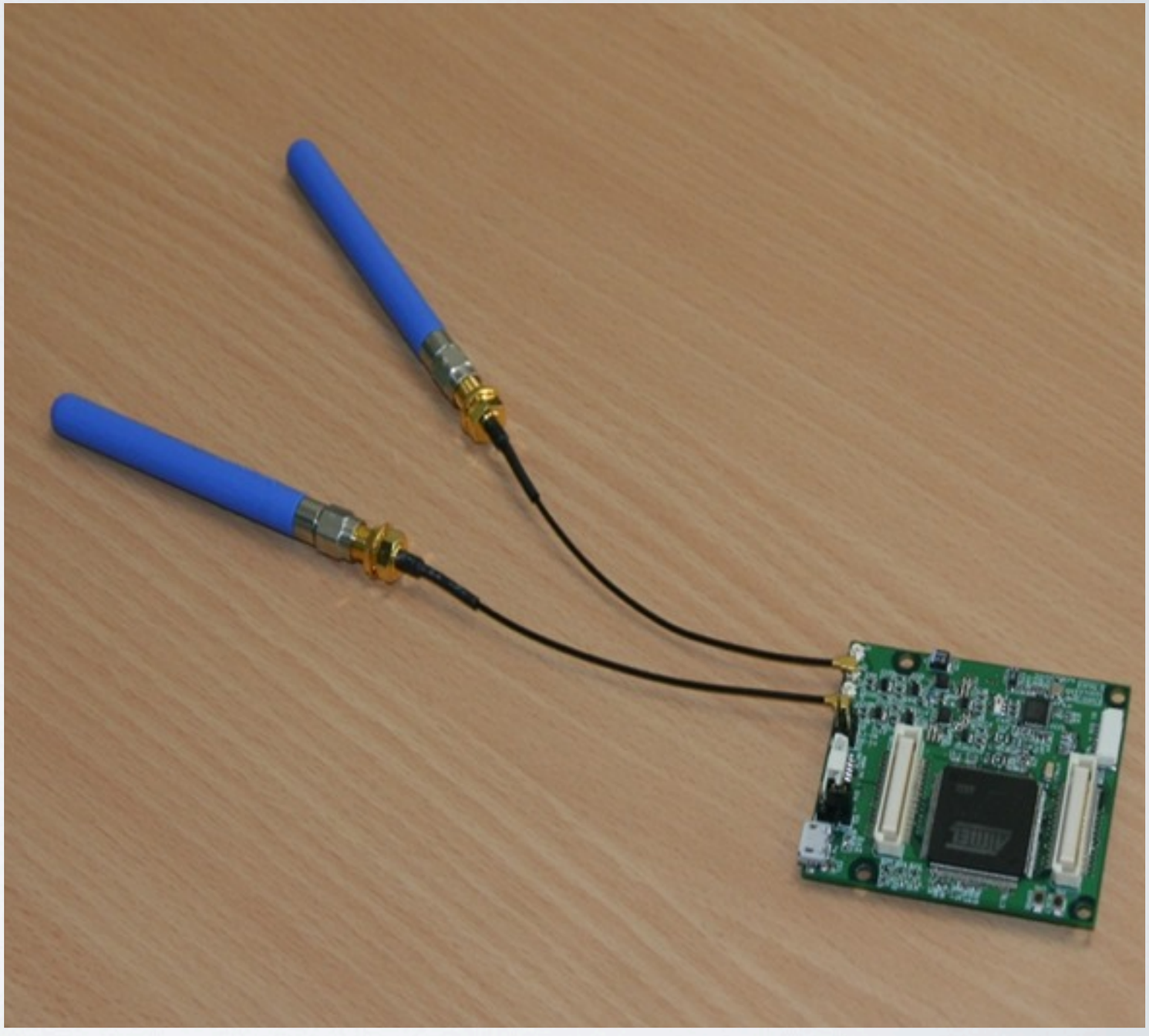
Thursday, 16 February 2012

The CSIRO's Opal Sensor Node

A next-generation WSN node. Dual-frequency dual-antenna.



R. Jurdak, K. Klues, B. Kusy, C. Richter, K. Longendoen, M. Bruenig. "Opal: A Multi-radio Platform for High Throughput Wireless Sensor Networks", IEEE Embedded Systems Letters, December 2011.



Current Practices to Improve Link Reliability

- Careful selection of node locations
  - Hand-place nodes for direct line of sight
- Over-provisioning
  - Link-level retransmissions (e.g., 30x by CTP)
  - Node spacing of one 20th or 50th of the expected radio range
  - Placement of additional forwarders in poorly connected areas
  - Use of high gain directional antennas for communication backbone
- Consequence: increased cost and time to deploy sensors!!!

Improving Link Robustness Through Diversity

Frequency diversity

- Embrace wide-band solutions
- Operate multiple radios simultaneously to avoid synchronization complexity

Spatial diversity

- Use multiple antennas
- Connect each radio to a separate antenna

Time diversity

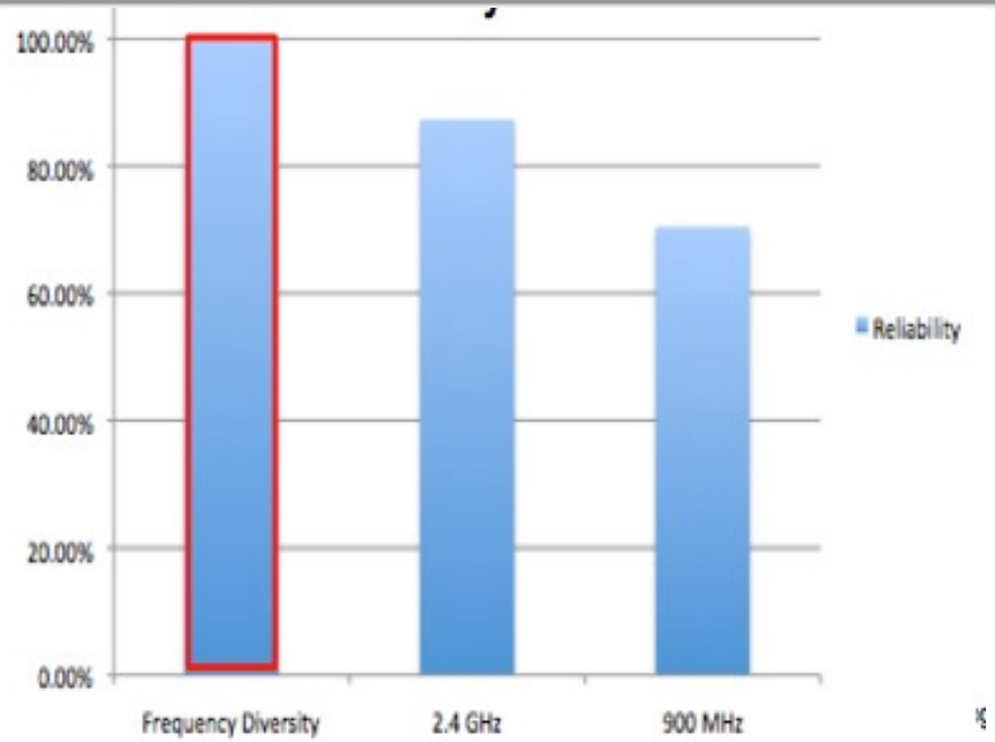
- Spreading, done by 802.15.4 chips already

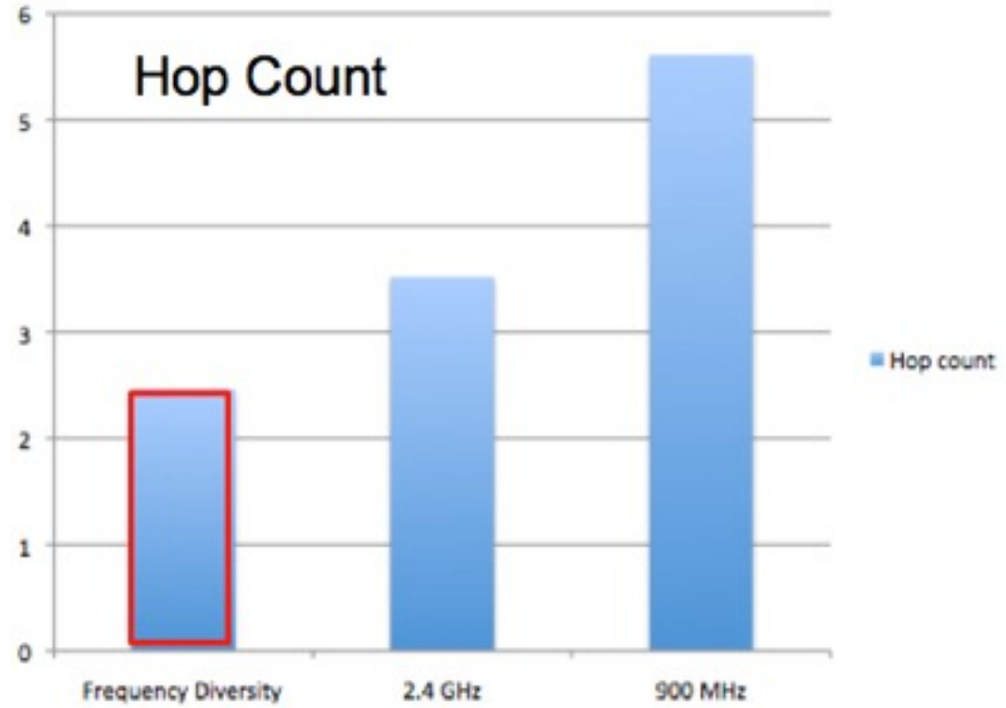
Our reference architecture

- Use two 802.15.4 radio chips
- Radio frequencies separated by 1.5GHz
- Antennas separated by 0.5m

Metric	AT86RF212	AT86RF230
Frequency	779-787MHz 863-870MHz 902-928MHz	2405-2480MHz
Data rates	BPSK: 20, 40 kbps, O-QPSK: 100, 200, 250, 500, 1000 kbps	O-QPSK: 250 kbps
TX power	-11 to 10 dBm	-17 to 3 dBm
Sensitivity (250kbps)	-101 dBm	-101 dBm
Link budget (250kbps)	111 dBm	104 dBm

The CSIRO's Opal Sensor Node





B. Kusy, C. Richter, W. Hu, M. Afanasyev, R. Jurdak, M. Bruenig, D. Abbott, C. Huynh, and D. Ostry. "Radio Diversity for Reliable Communication in WSNs," In Proceedings of the 10th International Conference on Information Processing in Sensor Networks (IPSN), Chicago, USA, April, 2011.

Implementation

Dual radio driver in TinyOS

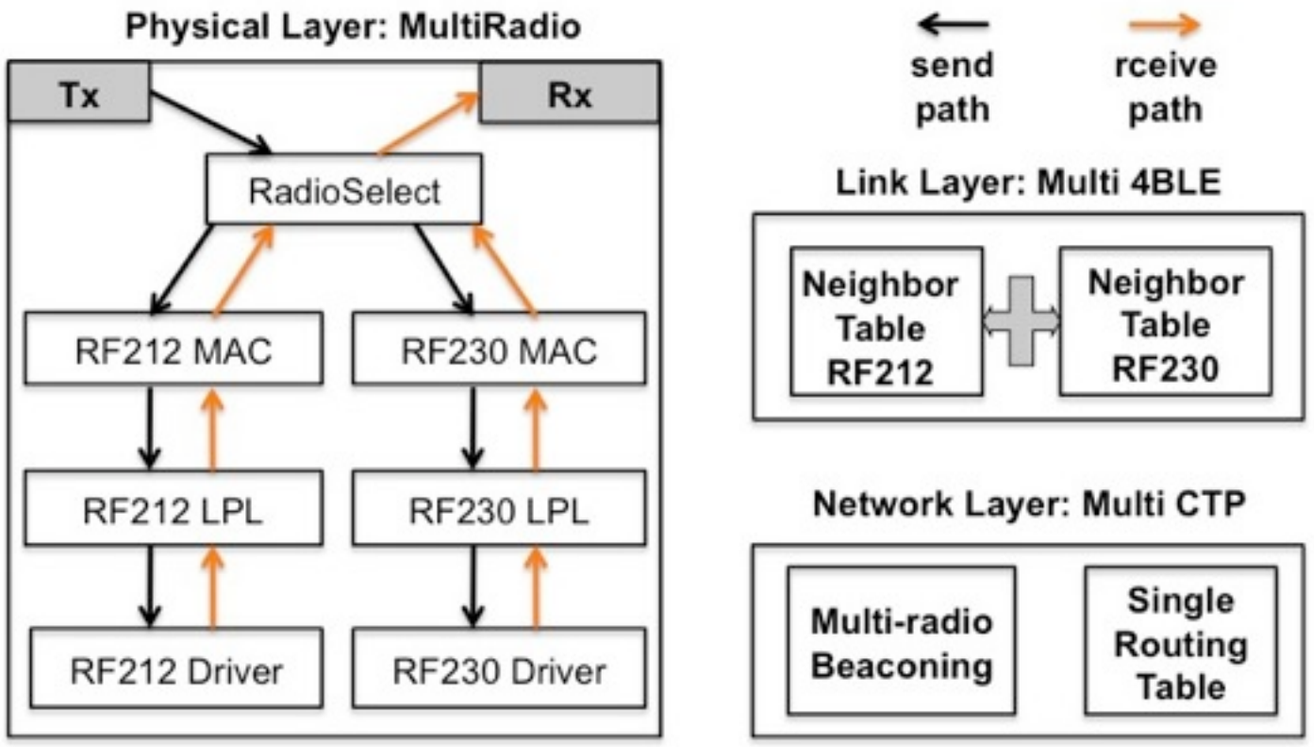
- Sleep, transmit, receive packets independent of each other

Link estimation and data collection layers

- Extended to work with multiple radios, two neighbor tables, etc

Conform to standard TinyOS interfaces and packet headers

- Our platform works with existing applications and deployments!!!



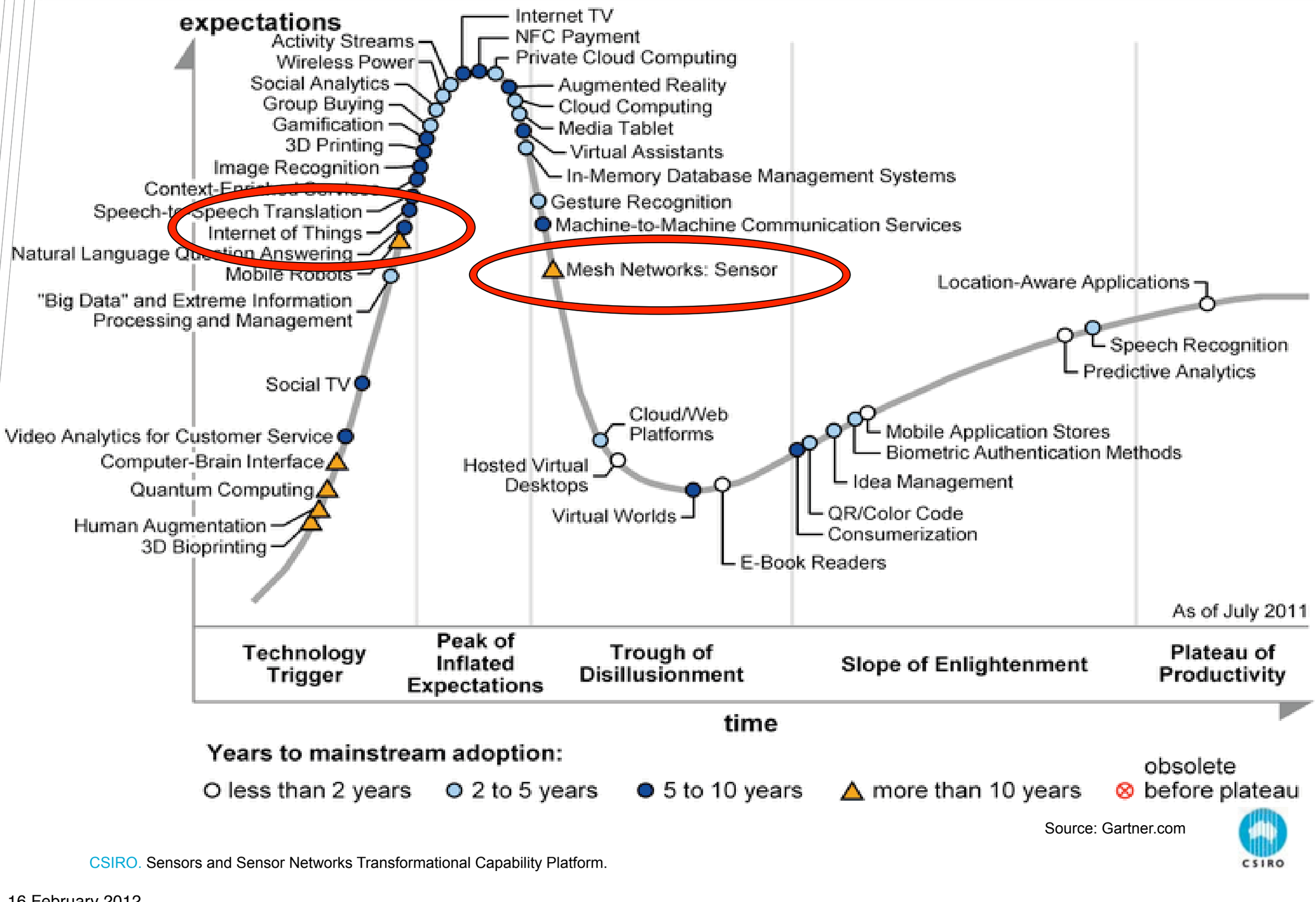
Real progress over the decade

- Communications
  - Radio hardware
    - 802.15.4 standard, more sensitive receivers, duty cycling, encryption, bigger packets, higher bit rate, support for TOF measurement
    - more than one radio per mote, more than one antenna per radio
    - Protocols, IPv6
- Mote software, Contiki & TinyOS, widely used, large user communities, good platform support, threads
- Processor, moving beyond AVR and MSP; 32 bit, frequency scaling on the horizon
- Energy: processor consumption has fallen, more efficient algorithms, energy harvesting is real (vibration, solar etc)
- Testbeds
- Simulation tools (communications, protocols, energy etc.)

Areas for future work

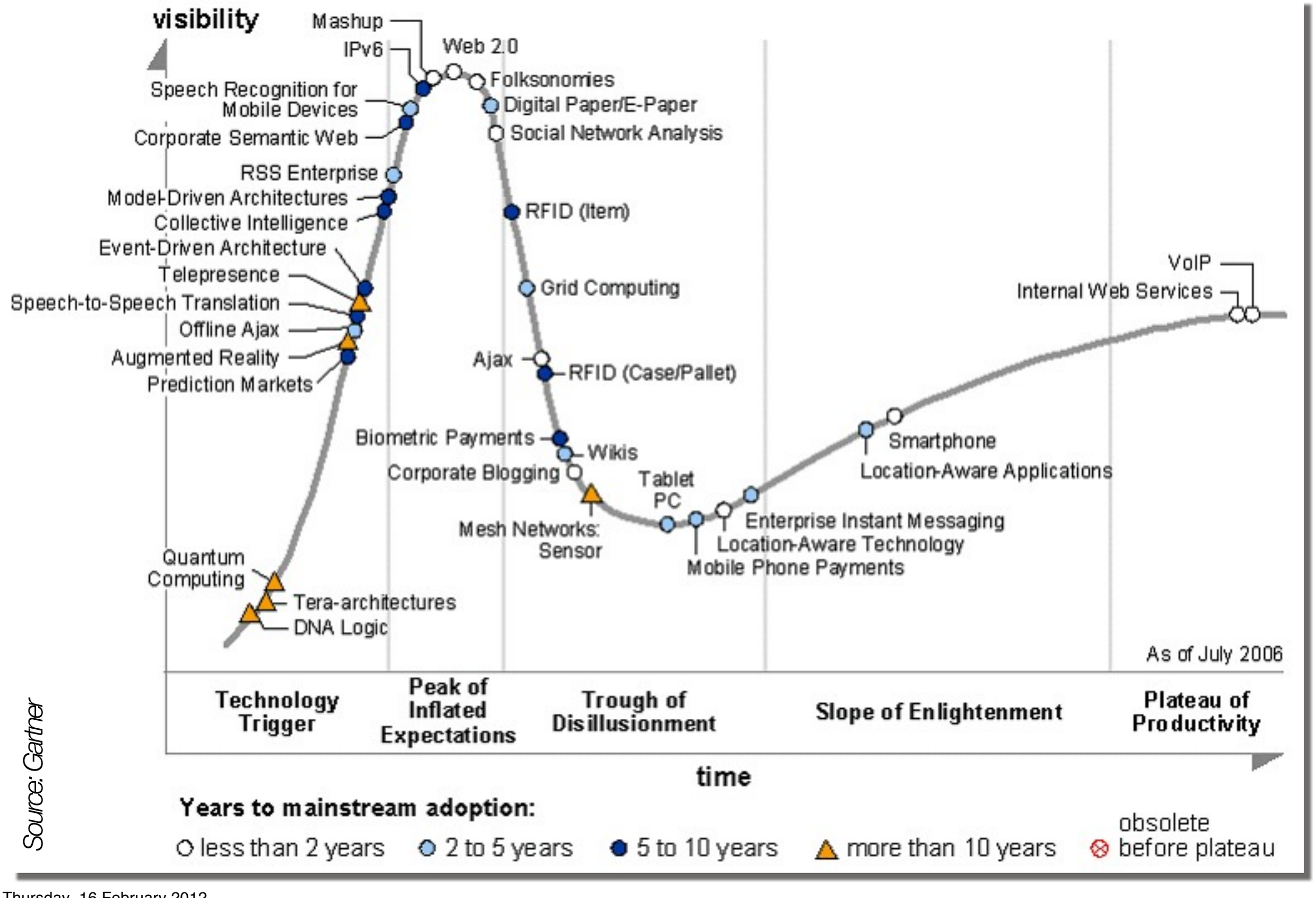
- Secure reprogramming and network control
- Automatic network diagnosis
- Pre-deployment planning tools
- In-situ audio and video processing
- Automated data collection, robots and sensor networks as appropriate and integrated
- Task-level programming, stop programming the mote
- Visualization and mining of sensory data streams
- Mobile phone class processors: Cortex + DSP + GPU

Gartner Hype Cycle



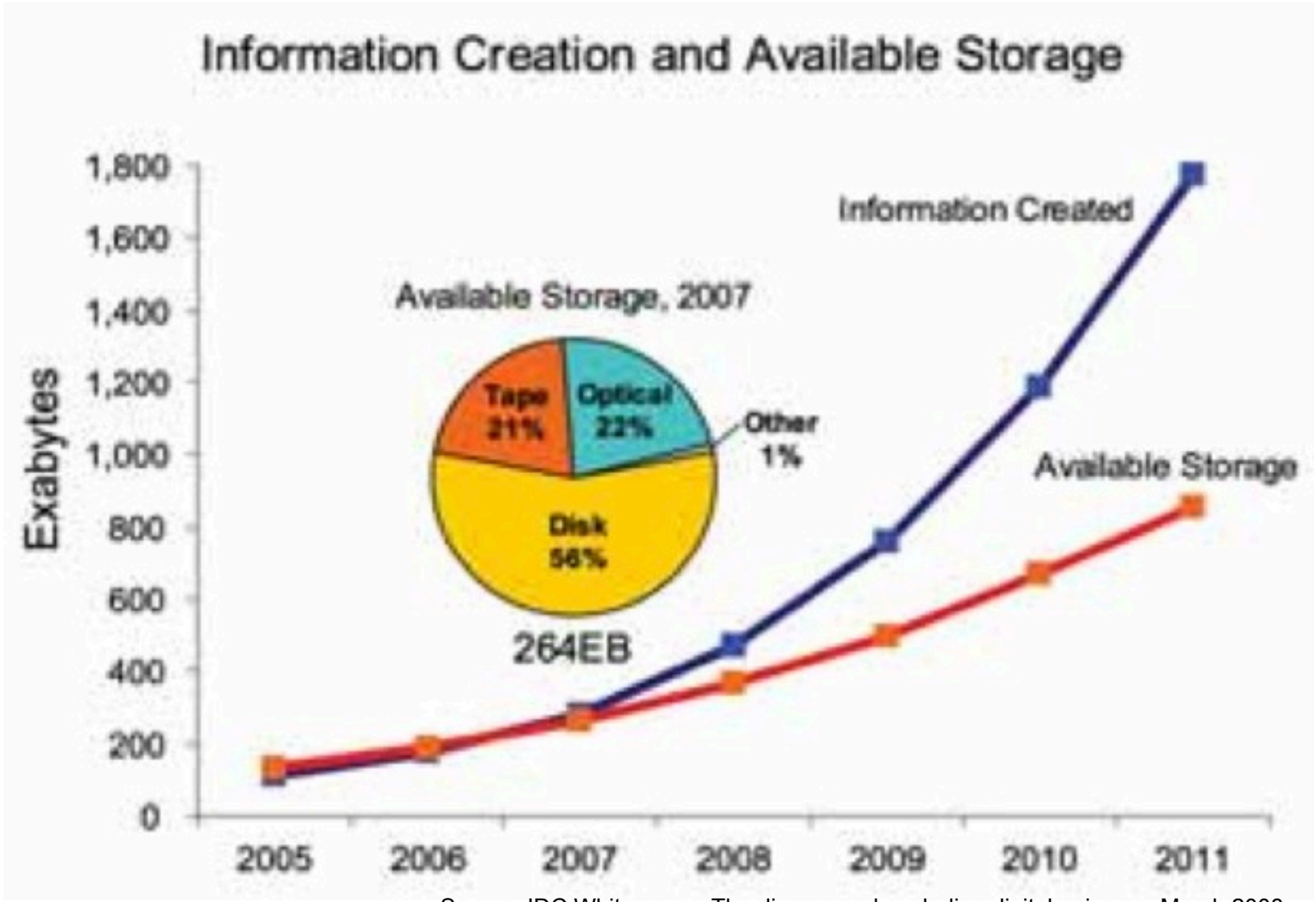
Source: Gartner.com

The Hype Cycle



Source: Gartner

Information Creation vs. Available Storage



Source: IDC White paper, The diverse and exploding digital universe, March 2008

Engagement Opportunities

- Students
  - Full scholarships
    - **Endeavour Postgraduate Fellowships:** provide financial support for international students for up to 4 years to undertake a postgraduate qualification at a Masters or PhD level in Australia (applications due in June)
  - Internship support
    - **Endeavour Research Fellowships:** support research towards a Masters degree or PhD in home country; or postdoctoral research (applications due in June)
    - **CSIRO traineeships:** support research towards a Bachelors, Masters or PhD in home country (applications open)

- Faculty
  - Distinguished Scholar Visits
    - Research-oriented
    - 3-12 months
  - Endeavour Executive Awards
    - Professional development
    - 1-4 months
  - Joint proposals through international funding schemes
  - Resource (hardware) sharing for joint research
    - Currently sharing nodes with MIT, ETH-Zurich, TUM, Johns Hopkins, TU Delft..

CyPhy Lab

Cyber-Physical Systems Lab
Queensland University of Technology

https://wiki.qut.edu.au/display/cyphy

CSIRO

http://sensornets.csiro.au

Questions?

or email me: peter.corke@qut.edu.au