Potential Use of Nanosatellites for Store-and-Forward (S&F) Remote Data Collection Systems

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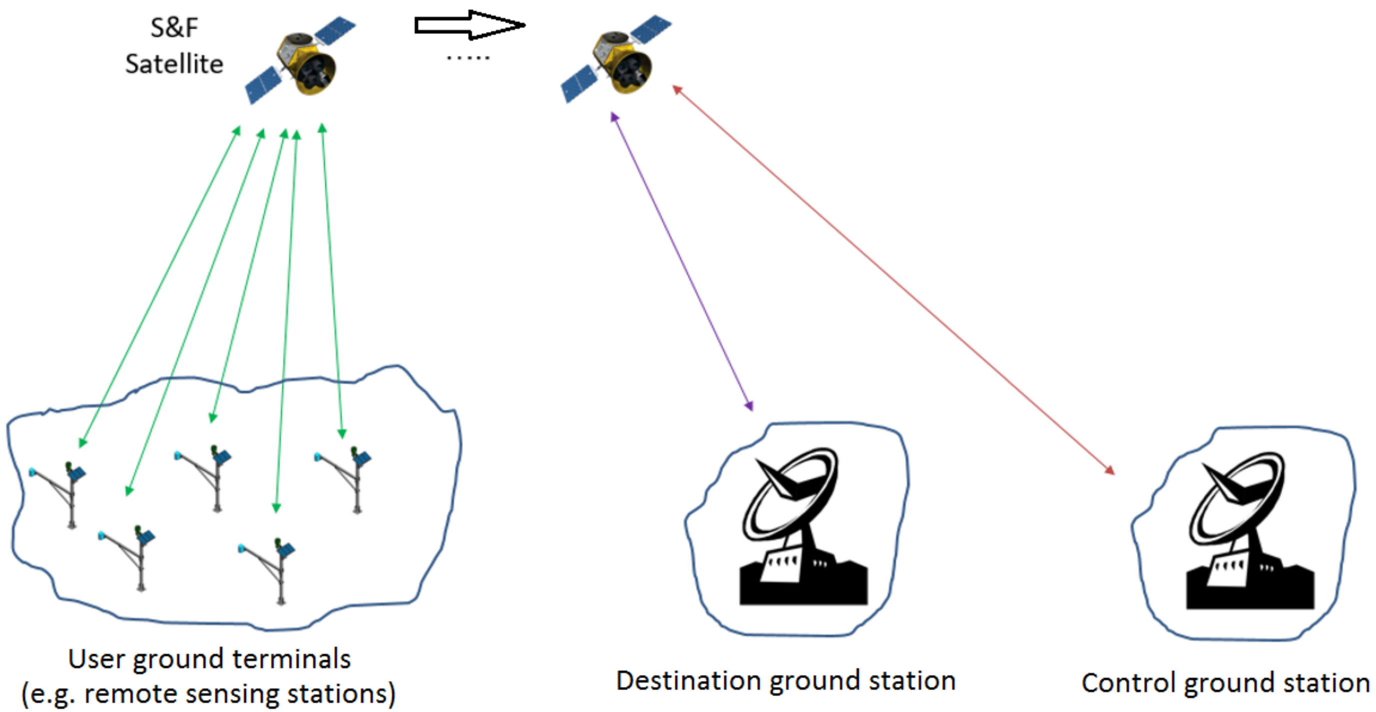
Presentation Outline

- Background: Satellite Store-and-Forward (S&F) System
- Recent S&F Remote Data Collection Systems and Applications
  - Examples of nanosatellite S&F based remote data collection systems
- Overview of the BIRDS-2 S&F Mission
  - Technical challenges: enabling the nanosatellite S&F remote data collection system
- Other Futuristic Concepts
  - *"Internet of Remote Things"* (IoRT) / "Internet of Space"
  - Nanosatellite-linked *Wireless Sensor Networks*
  - *Data Mules*: data routing in cubesat/nanosat/picosat constellation S&F systems
- Conclusion

Background on Satellite Store-and-Forward (S&F) System

Components of a Satellite S&F System

- A spacecraft that "receives and stores messages while over one part of the earth and downloads them later over another part of the globe." [1]

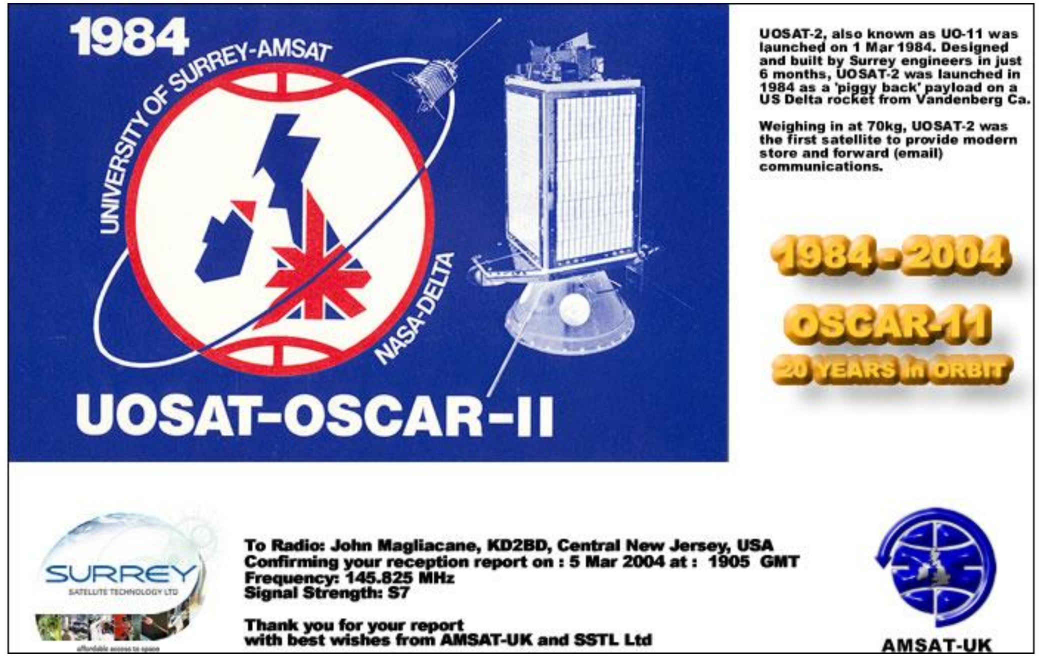


Basic components of a satellite store-and-forward system

[1] K. Martin, V. Venkatesan and U.N. Das, "Data Link Control in the LEO Satellite Store and Forward Network", IEEE, 2003.

Early Development Work

- From early 1980s to 1990s
  - Amateur radio researchers/experimenters pioneered the design of simple, small-size, efficient and low-cost digital S&F communication satellites [2]
  - March 1984 – launch of the first S&F microsatellite UoSAT-2



Source: http://www.qsl.net/kd2bd/kd2bd.html

[2] R. Diersing and G. Jones, "Low Earth-Orbit Store-And-Forward Satellites in the Amateur Radio Service", IEEE AES Systems Magazine, January 1993.

Satellite	Launch date	Communications Payload	Uplink	downlink
UoSAT-2	1984	First store and forward mission 1200baud AFSK 128kbyte memory	VHF Amateur Service	VHF/UHF Amateur Service
UoSAT-3	1990 (1)	Store and Forward 4Mbyte filestore 9600baud FSK digitally filtered HealthNet/VITA	VHF Experimental	UHF Experimental
UoSAT-5	1991	Store and Forward 13Mbyte filestore 9600baud FSK digitally filtered	VHF Amateur Service	UHF Amateur Service
S-80/T	1992 (2)	Store and Forward 16Mbytes filestore 9600baud FSK digitally filtered transparent measurement transponder*	VHF Experimental (WARC-92) 148/150MHz	UHF Experimental (WARC-92) 137/8MHz
KITSAT-1	1992	Store and Forward 16Mbyte filestore 9600baud FSK digitally filtered DSP experiment using TMS320C25/C30 provides capability for adaptive modulation	VHF Amateur Service	UHF Amateur Service
PoSAT-1	1993	Store and Forward 16Mbyte filestore 9600/38400 FSK digitally filtered DSP experiment includes MSK downlink option and adaptive modulation capability	VHF Experimental	UHF Experimental
KITSAT-B	1993	Store and Forward 16Mbyte filestore 9600baud FSK digitally filtered	VHF Amateur Service	UHF Amateur Service
HEALTHSAT-2 (3)	1993	Store and forward 3x16Mbyte filestore 9600/38400 FSK digitally filtered Adaptive transmit power under on board computer control	VHF (WARC-92)	UHF (WARC-92)
For launch 1995				
CERISE	1995	9k6/38k4baud	VHF	UHF
FaSAT-Alfa	1995	Store and Forward 9k6-76k8baud FSK DSP communications payload	VHF	UHF

Fig. 2. Experimental and amateur S&F satellites in1980s and 1990s (Source: [3])

[3] M.N. Allery, H.E. Price, J.W. Ward, and R.A. Da Silva Curiel, “Low Earth orbit microsatellites for data communications using small terminals”,

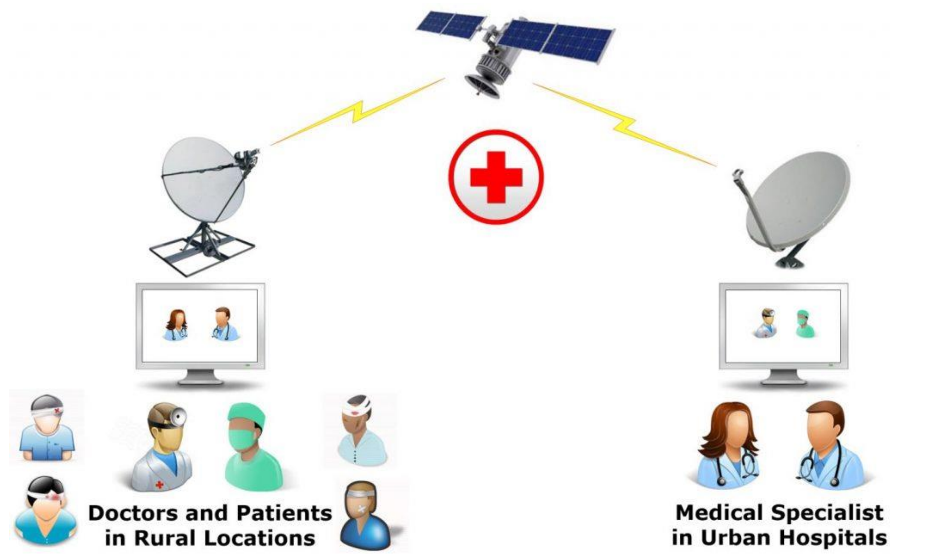
Early Development Work

- Purpose and Roles [2, 3]
  - Enable *non-real-time* communication, *low data* transfer rate and volume (~up to a few tens of kbps)
  - Provide personal communication services to amateur community such as email & file forwarding, messaging and broadcasts.
  - Formed the *basis* of both experimental and operational microsatellite missions for remote site data collection and messaging
  - *Complementary roles of small systems for specialized services*
    - ‘Big’ LEO systems’ focus had been to provide global mobile communications.

[2] R. Diersing and G. Jones, “Low Earth-Orbit Store-And-Forward Satellites in the Amateur Radio Service”, IEEE AES Systems Magazine, January 1993.
[3] M.N. Allery, H.E. Price, J.W. Ward, and R.A. Da Silva Curiel, “Low Earth orbit microsatellites for data communications using small terminals”,

Recent S&F Systems: Niche Applications

- Later on – development of commercial communication satellites offering similar services (ORBCOMM, Iridium, GONETS, KITComm, etc.)
- Current systems providing *higher data capacity* to support niche markets [4]
  - Tele-learning
  - Data transfer to/from remote sites
    - Remote environment monitoring,
    - Automatic sensor/meter reading
    - Transmission of documentary films from remote zones
    - Military/warfare communications
  - Tele-control of remote instrumentation
    - Scientific experiments in Antartica
  - Tele-medicine



VSAT satellite improves health services in rural areas (Source: http://www.vizocomsat.com/blog/importance-vsat-satellite-services-telemedicine/)

[4] M. Antonini, et. al., "Satellite Data Collection & Forwarding Systems", IEEE A&E Systems Magazine, September 2005.

Data Requirements of Various Services

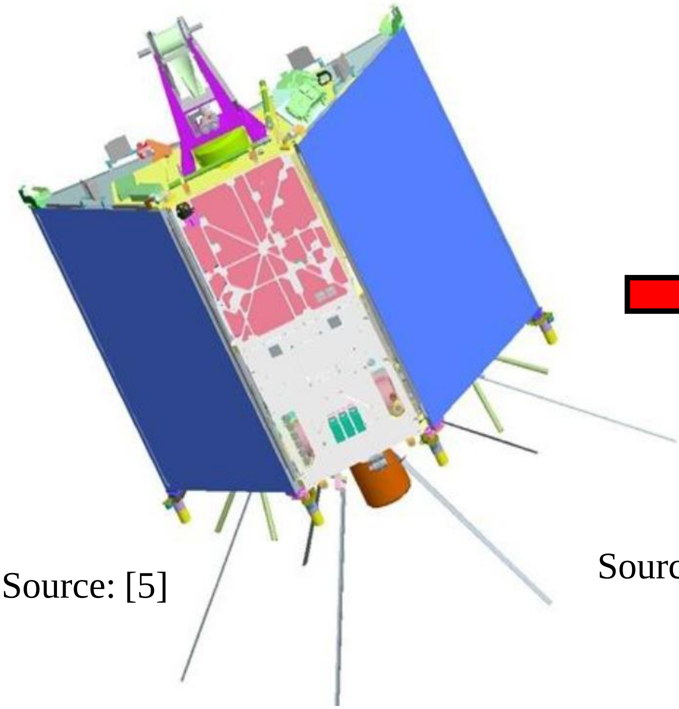
Service	Delay	Coverage	Data Rate	Memory (Data Volume Range)
Telemedicine	6+24 hours	World	~ Mbps	~ 100 Mbyte
Business data	6+24 hours	Urban	~ Mbps	~ 1 Gbyte
Infomobility	Few hours	Country	~ 100 kbps	~ 100 Mbyte
Fleet management	Few minutes	Continent	~ 100 bps	~ 1 Mbyte
Automatic meter or sensor reading	12+48 hours	Country	~ 100 bps	~ 1 Mbyte
Audio and video transfer	6+24 hours	World	~ Mbps	~ 1 Gbyte
Multimedia books	1 week	Continent	~ Mbps	~ 100 Mbyte
Military applications	Few hours	Territory	~ 10 Mbps	~ 1 Gbyte

Table Source: [4] M. Antonini, et. al., “Satellite Data Collection & Forwarding Systems”, IEEE A&E Systems Magazine, September 2005.

Recent S&F Remote Data Collection Systems and Applications:

Examples of nanosatellite S&F-based remote data collection systems

Trending: From Micro- to Nanosatellite S&F Systems



Source: [5]

Sina-1 [5] (launched 2005, Iran, **160 kg**, 682 km x 704 km)

Source: [6b]

ANUSAT [6] (launched 2009, ISRO & ANU, India, **38 kg**, 550 km)

Source: https://www.youtube.com/watch?v=yL5ATJKSRLk

WAPOSAT [7] (launched after 2012, UNI and WAPOSAT company, Peru, **<5 kg, 2U** cubesat constellation, 1000 km

[5] D. Abbasi and M. Abolghasemi., "Store & Forward Communication Payload Design for LEO Satellite Systems ", Majlesi Journal of Electrical Engineering, Vol. 10, No. 3, September 2016.

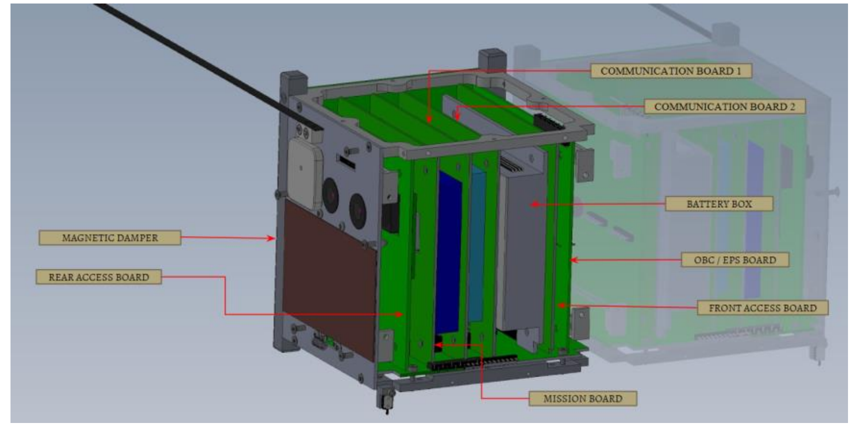
[6] V. Vaidehi, S. Muthuselvam, et.al., "Software Design of Store and Forward Payload for a Microsatellite", Dept. Electronics Engineering, Madras Institute of Technology, Anna University, India. (also: [6b] https://directory.eoportal.org/web/eoportal/satellite-missions/a/anusat)

[7] H. Bedon, G. Rodriguez, C.Negron, "Global water pollution monitoring using a nanosatellite constellation", Universidad Nacional de Ingrenieria, Peru, published in Research Gate on March 2014.

Trending: From Micro- to Nanosatellite S&F Systems

Source: [8]

Irazu cubesat [8] (under development, expected launch: 2017, TEC, Costa Rica, **1U** cubesat, 400 km)



Source: BIRDS-2 Project

BIRDS-2 cubesats [9] (under development, expected launch: 2018, Kyutech, Japan, Bhutan, Malaysia, Philippines,
3-member **1U** cubesat constellation, 400 km)

[8] "Irazu Project: The First Satellite Made in Costa Rica", posted in KickStarter, https://www.kickstarter.com/projects/irazu/irazu-project-the-first-satellite-made-in-costa-ri
[9] "BIRDS-2 S&F Mission: Demonstration of a Cubesat Constellation Store-and-Forward (S&F System)" by Adrian Salces, an article published in BIRDS Project Newsletter, Issue No. 15, April 2017 (Editors: G. Maeda, T. Taiwo, J. Javier, M. Cho)

WAPOSAT [7]

- Water Pollution Monitoring Using a Nanosatellite Constellation

- Need
  - Lakes and rivers in Peru lack pollution detection mechanisms for protecting them from metal wastes (industrial, mining & other activities)
  - Affecting physio-chemistry water characteristics

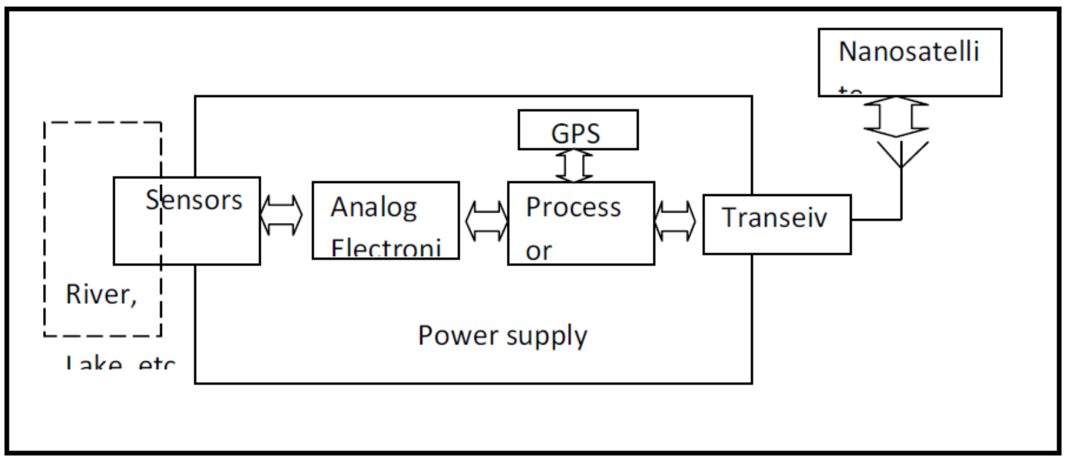
Video: https://www.youtube.com/watch?v=yL5ATJKSRLk

[7] H. Bedon, G. Rodriguez, C.Negron, “Global water pollution monitoring using a nanosatellite constellation”, Universidad Nacional de Ingrenieria, Peru, published in Research Gate on March 2014.

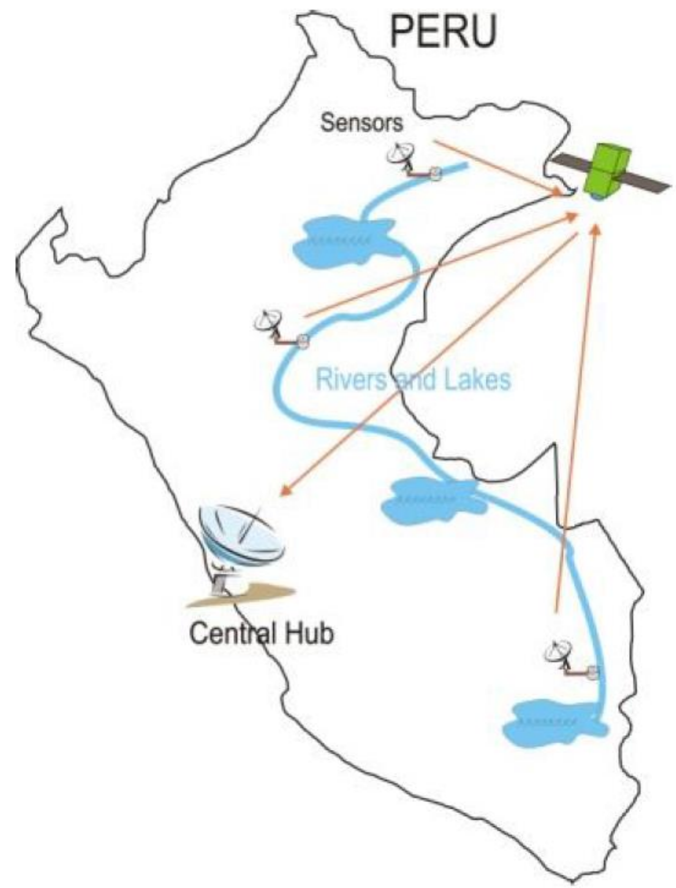
WAPOSAT [7]

Objectives

- Retrieve water pollution information from sensors (pH, oxygen conc., temp., fluidity, etc.) distributed over Peruvian lakes and rivers.
- Send the retrieved data from sensors to ground stations and then to a satellite (constellation).
- Distribute the data from the satellite constellation to every monitoring center for analysis.



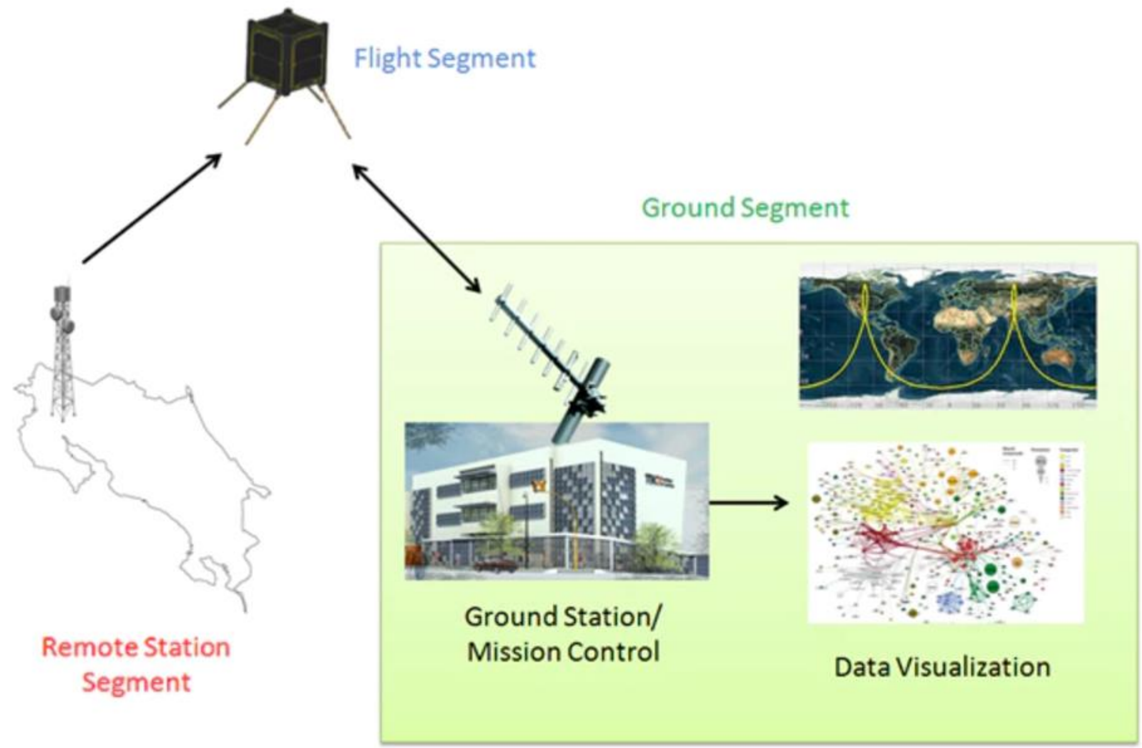
Autonomus multi-sensor system (AMSS) diagram



Mission concept. Data from polluted water is sent to a Central Hub in Lima through satellites [7].

Irazu Project

- **Mission**
  - *"To develop a full life cycle space engineering project using CubeSat technology as a proof of concept of a communication platform able to transmit environmental variables measured from remote protected areas in Costa Rica's territory to a data visualization center for climate change research."* [8]



Irazu project concept of operations. The overall system consists of three segments: remote station, flight and ground segments. The remote station will measure forest growth, carbon sequestration, humidity, other weather parameters. (Source: [8])

[8] "Irazu Project: The First Satellite Made in Costa Rica", posted at KickStarter, https://www.kickstarter.com/projects/irazu/irazu-project-the-first-satellite-made-in-costa-ri

Irazu Project

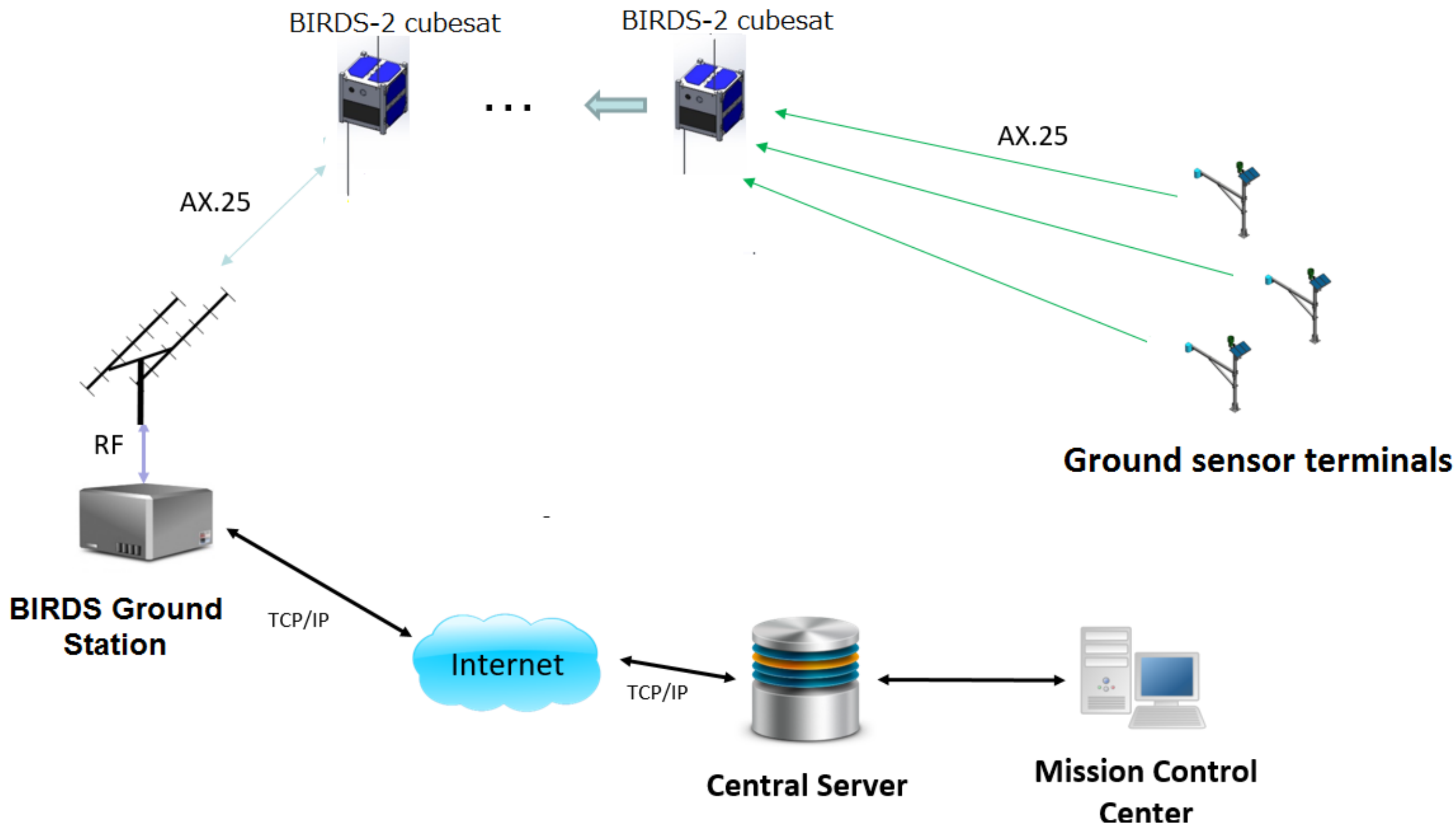
Video Source: [8] “Irazu Project: The First Satellite Made in Costa Rica”, posted at KickStarter, https://www.kickstarter.com/projects/irazu/irazu-project-the-first-satellite-made-in-costa-ri

Overview of the BIRDS-2 S&F Mission

BIRDS-2 S&F Mission Objectives

- To demonstrate a cubesat constellation store-and-forward remote data collection system.
- To investigate communication and other technical challenges of such system.
  - Tight constraints on transmit power, satellite visibility duration and power constraint
  - Experiments on appropriate data format, multiple access scheme, data handling
- To collect data from selected remote ground sensor terminals, store onboard satellite memory, download to any BIRDS ground station, and compile and process at a mission center.

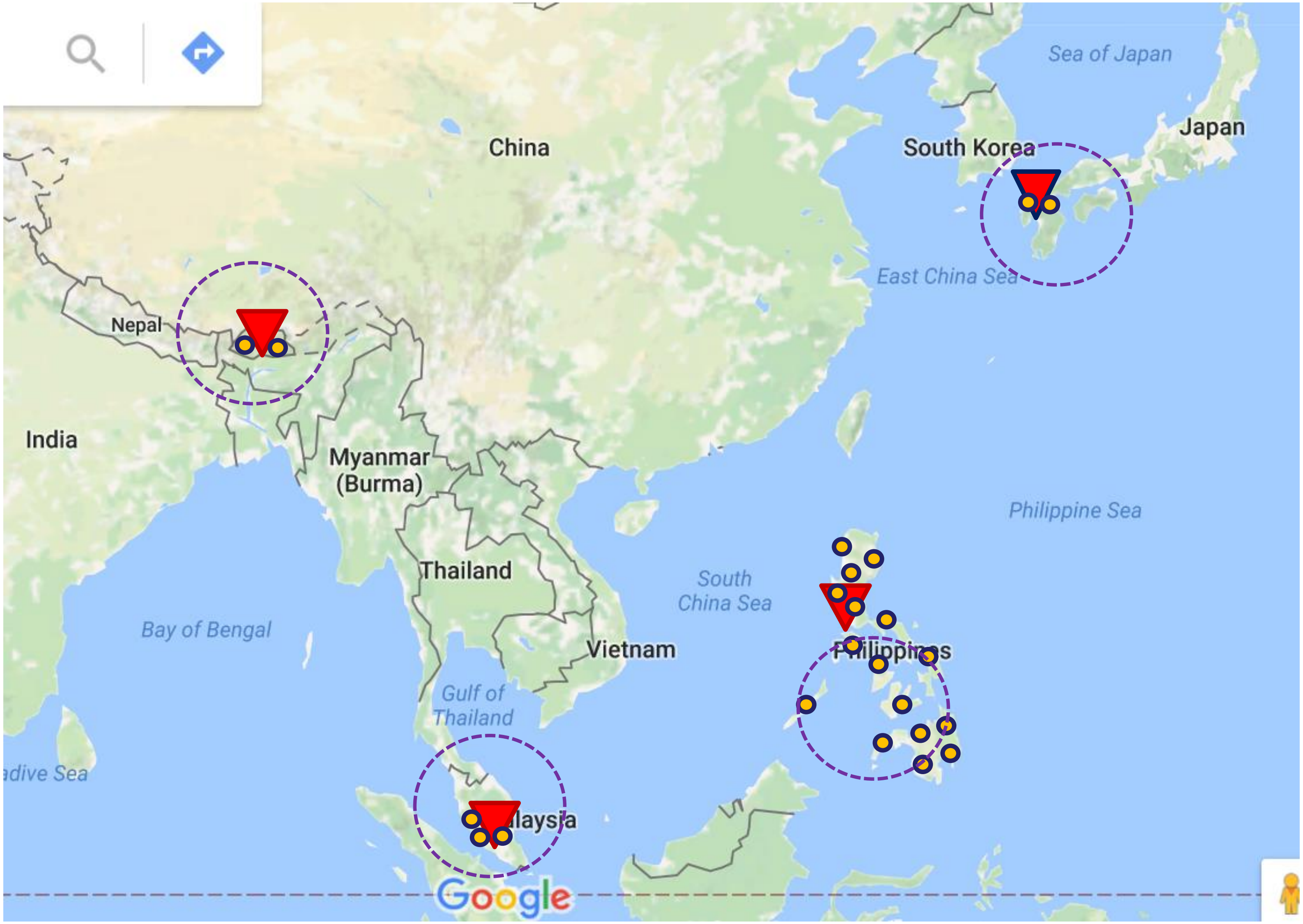
Overview: Proposed BIRDS-2 S&F System



Main Components:

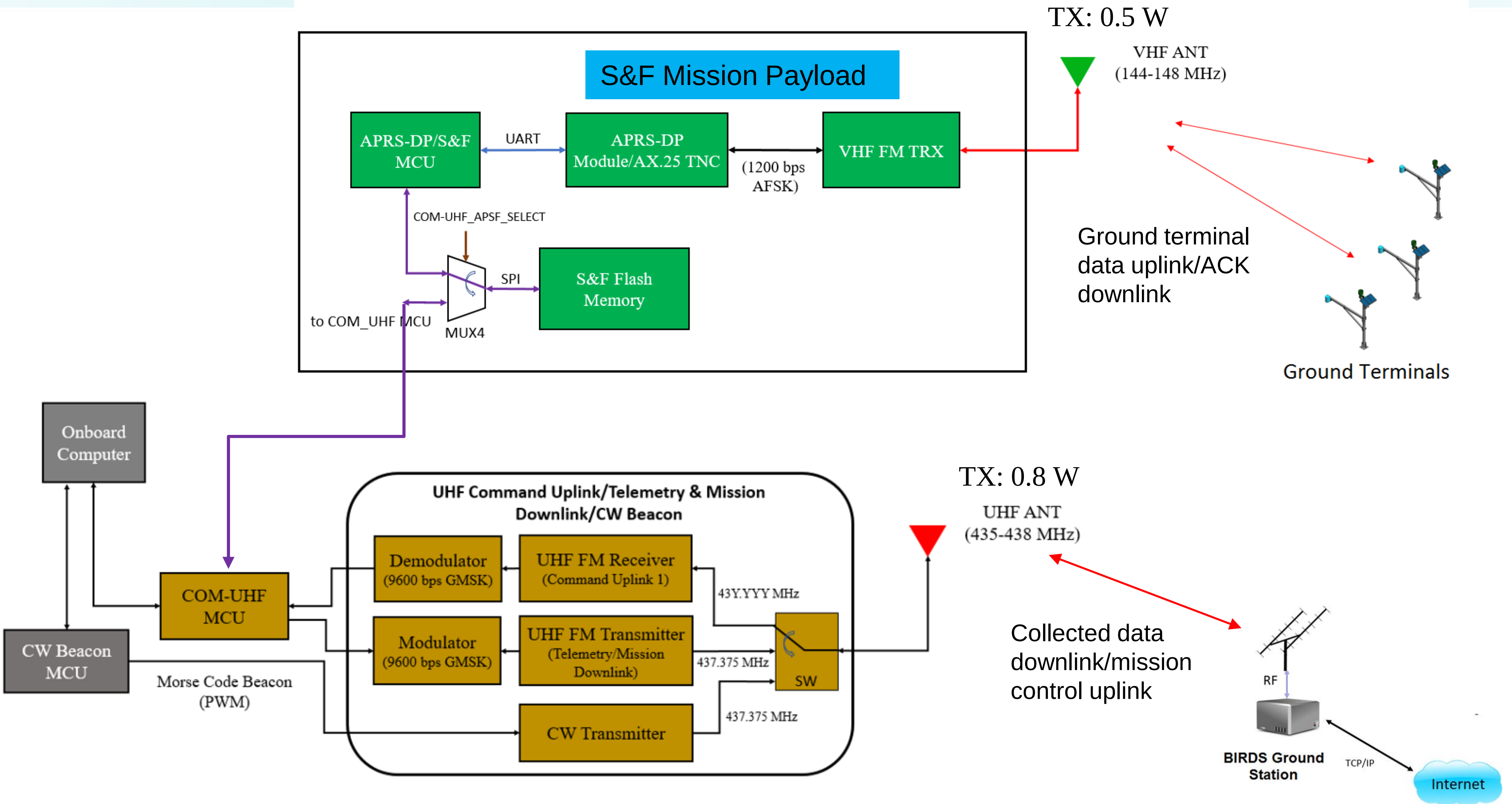
- Ten (10) BIRDS-2 ground stations connected to a central server and mission control center through the Internet
- Three (3) 1U cubesats
- Several ground sensor terminals distributed in a wide geographical area

Geographically Dispersed Ground Terminals



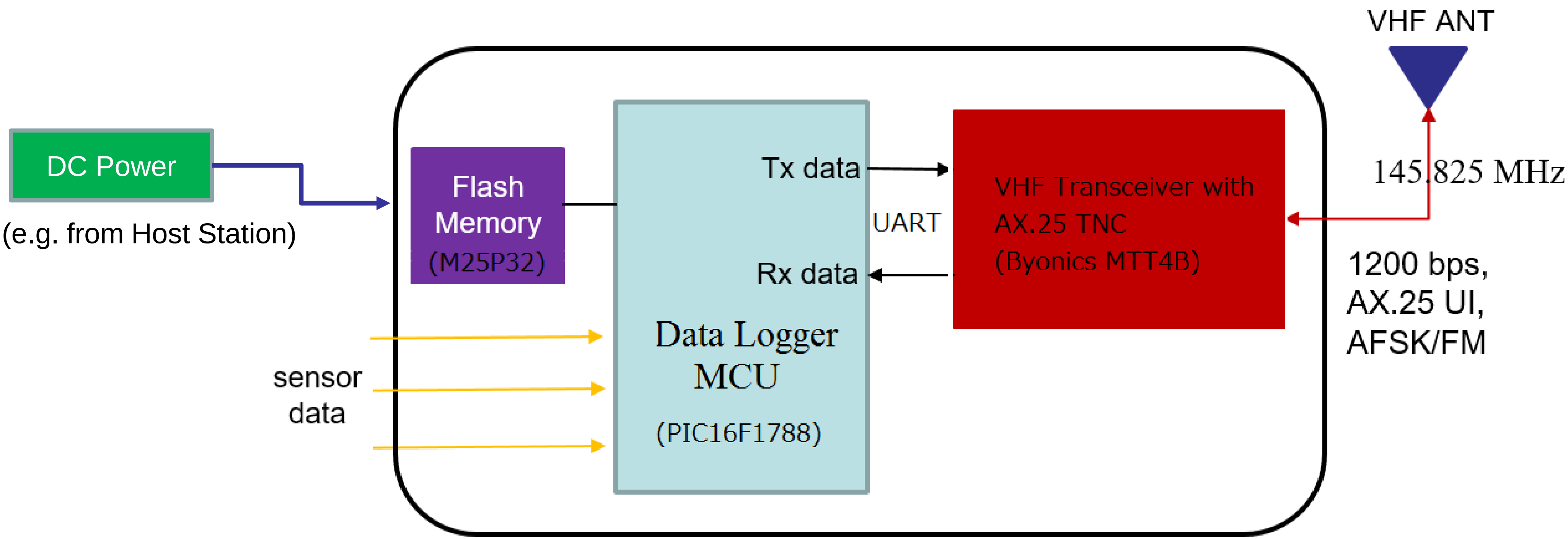
- Main control ground station and mission center at Kyutech
- BIRDS-2 Ground Stations at home countries
- *Sample* locations of ground sensor terminals
- Sample satellite moving footprint

Block Diagram of S&F Subsystem Onboard BIRDS-2 Cubesat



- S&F mission payload will have a very *simple architecture* given that the satellite has five other missions. Components e.g. transceiver, MCUs, etc. are mostly low-cost COTS.

Ground Sensor Terminal Implementation

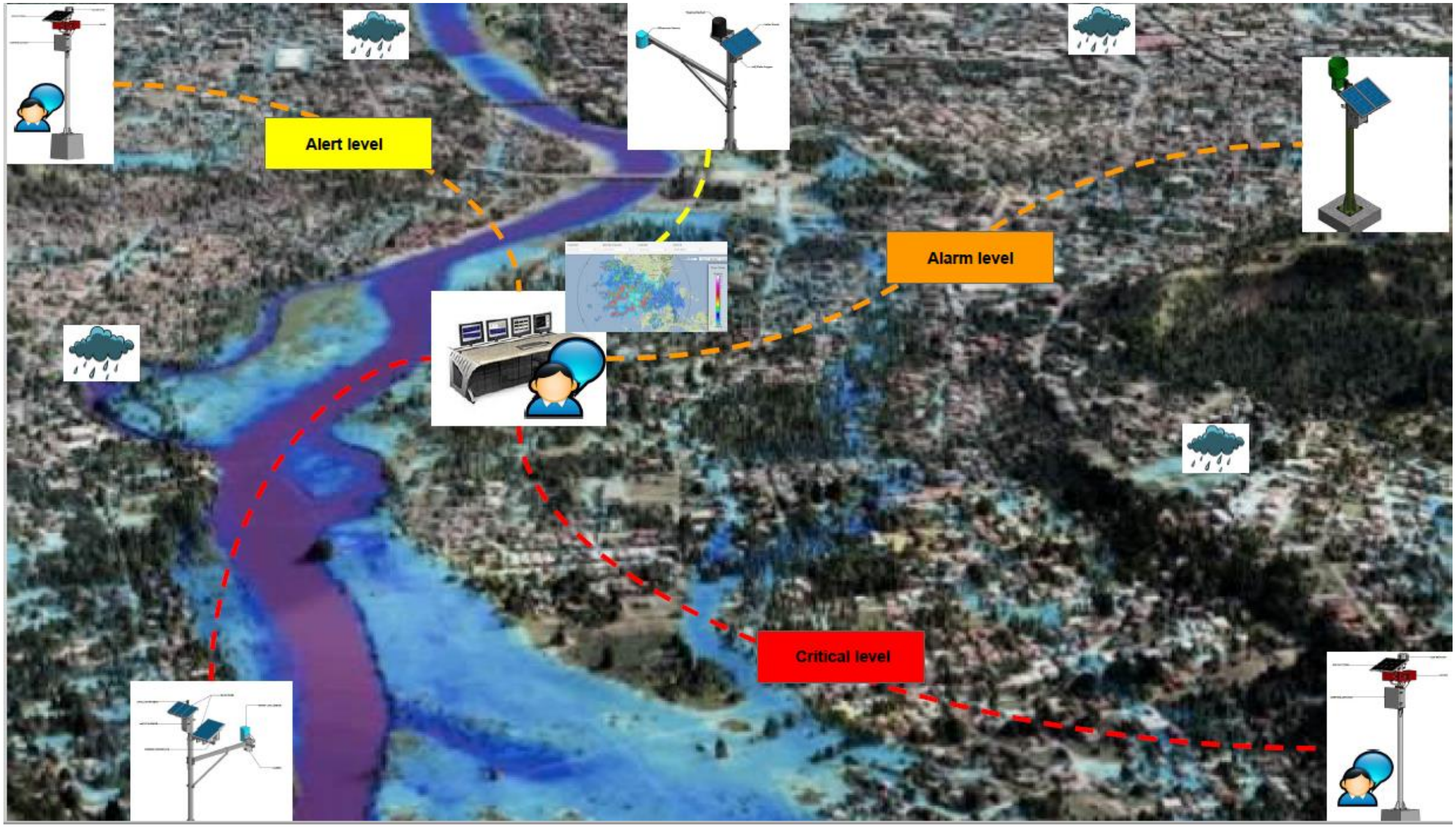


- This ground sensor terminal module (GSTM) will be either interfaced to an existing host station (with sensors) or stand-alone.
- Transmit power of transceiver: up to **8 W**

Weather Monitoring Stations (Philippine Case)

Courtesy of Joven Javier, DOST ASTI

Weather Monitoring Stations (Philippine Case)



Courtesy of Joven Javier, DOST ASTI

- Automated weather stations are deployed in strategic locations such as rivers and other bodies of water.

Weather Monitoring Stations (Philippine Case)

- Sample data format of weather station (water level with rain gauge case)
  - Data logging once every 15 minutes
  - Data size varies in every station, normally < 100 bytes each (per log)
  - <9.6 kilobytes/station/day

8.34+0+0+10132.5+4.0+4.0+0.000+0.000+0.000+1010+21+27.3+50.7+0+150826/13:00:00

1. sensor data (in meters)
2. Rain value (in no. of tips)
3. Rain cumulative
4. Station Pressure
5. Power Board 1 Battery level
6. Power Board 2 Battery level
7. Current monitoring
8. Power Board 1 Boost voltage
9. Power Board 2 Boost voltage
10. Charging status
11. GSM signal level
11. arQ temperature
12. arQ Humidity
13. arQ flash page
14. Date and Time

Courtesy of Joven Javier, DOST ASTI

Technical Challenges: Nanosat S&F RDC Systems

- Limited satellite visibility and moving coverage
  - Collect data from as many ground terminals as possible
  - Multiple access scheme based on priority, fairness or schedule
    - Intelligent GSTs: Implement orbit calculator for efficient use of communication channel and energy
    - Antenna with tracking system is important, but is it avoidable?
  - Simplify/minimize communication exchanges:
    - Avoid/reduce reservation & acknowledgement frames

- Low data rate
  - Typically 1200 bps (e.g. BIRDS-2 case)
  - Simple and efficient (small overhead) data format is necessary.

Technical Challenges: Nanosat S&F RDC Systems

- Very tight communication link budget
  - Limited transmit power (~5 W uplink, 0.5 W downlink)
  - Increases required elevation angle => further reduces communication time
  - Unsymmetrical channel: requires an appropriate communication sequence to deal with it.

- Very simple architecture and limited capabilities of satellite onboard communication system and processor.
  - Communication protocols (e.g. multiple access, data link layer), data handling, encoding and modulation must be very simple.
  - For BIRDS-2:
    - AX.25 protocol, unconnected mode with application level ACK frames
    - AFSK on FM modulation, 1200 bps
    - Very cheap COTS components

Sample Data Frame Formats

	Other fields				Information Field			
Byte #	1	2-8	9-15	16	17	18-117	118-119	120
Content	Start flag	Satellite callsign	Ground terminal ID	Control PID	Packet sequence #	Sensor Data, time, etc.	FCS	End flag

Sample data frame format of the ground sensor terminal (using AX.25 frame format)

	Other fields				Information Field		
Byte #	1	2-8	9-15	16	17-21	22-23	24
Content	Start flag	Ground terminal ID	Satellite callsign	Control PID	ACK data	FCS	End flag

Sample format of ACK frame from the S&F communication payload (using AX.25 frame format)

Communication Scenario (Sample Case)

- 1 communication slot (excl. time for re-transmissions due to errors and assuming zero guard time)

$$\tau = T_{up} + T_{down} + T_{inf} + T_{ack} + T_{tr}$$

τ = 400 km/c +144*8 b/(1200 b/s) + 250 ms = **1.21 s**

$T_{up} + T_{down} = up\ \&\ downlink\ propagation\ delay$

$T_{inf} + T_{ack} = uplink\ and\ ACK\ packet\ duration$

$T_{tr} = processing\ delay$

- Visibility time per one location
  - Assumption: average visibility duration considering non-zero elevation angle = 3 minutes = **180 s**
  - Note: Total visibility time within a wider geographical area will be longer because satellite coverage gradually moves.

Communication Scenario (Sample Case)

- Total # of communication slots per location

$$N_{slots} = \frac{180s}{1.21s} = \mathbf{148\ slots}$$

- Assuming 80% frame transmission success rate
  - 148 slots * 0.80 **= 118 effective useful slots** (slots when data are successfully uploaded with ACK)

- Required slots per GST station
  - Assuming data logging every 30 minutes, 24/0.5 = **48 packets/day/GST**
  - Divided by 3 satellites with 2 passes each/day, 48/6 = **8 packets/GST/pass**

Communication Scenario (Sample Case)

- Average number of GST per location that can be accommodated per pass

$$N_{GST} = \frac{118}{8} = \mathbf{15\ GST/location}$$

- Note: Above analysis is very simplified. It is assumed that the satellite communicates only with 15 GST in one ground location only. In real scenario, GSTs are widely dispersed and the satellite coverage moves, which means that the satellite may be able to collect from other sensors in proximate or farther location. It is important to consider the satellite orbit for more correct analysis. Also, the analysis assumes that the GSTs upload data in a pre-scheduled sequence.

Other Futuristic Concepts

"Internet of Things (IoT)": The Next Industrial Revolution

Source: http://www.huffingtonpost.com/sam-cohen/internet-of-things-as-the_b_10937956.html

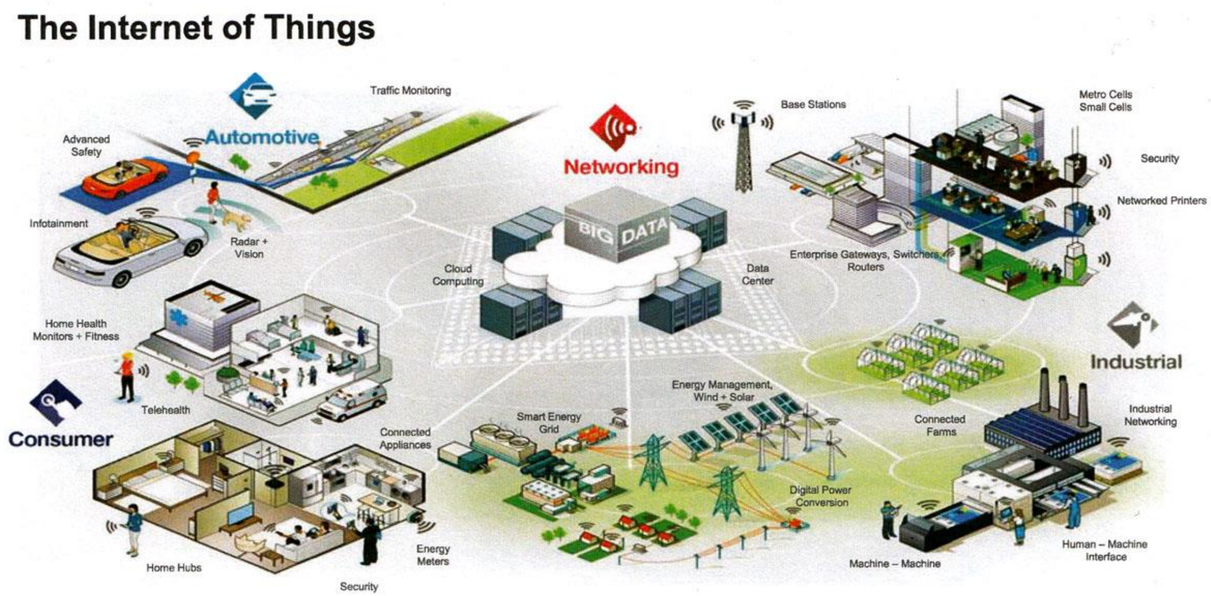
"Smart objects"

"Smart homes and cities"

"Technologies deeply embedded in environment and space"

"Ability to monitor and control distant objects [X]"

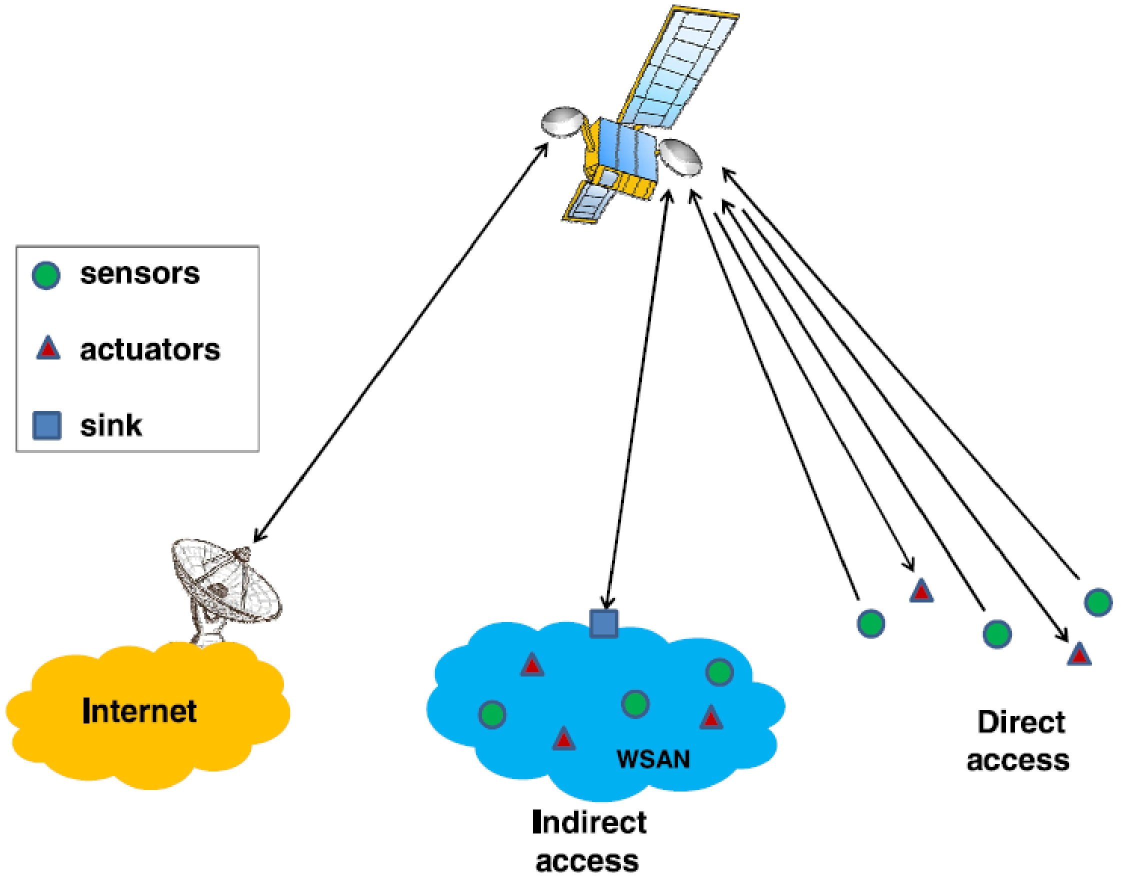
"Everything is connected to the cloud."



Source: [X] https://opentechdiary.wordpress.com/tag/internet-of-things/

"Internet of *Remote* Things (IoRT)", "Internet of Space"

- IoS: A future backbone for IoT [9]
- Satellites are crucial in connecting sensors and actuators distributed over very wide area or in remote areas not served by terrestrial networks [10].
  - Smart grids e.g. offshore farms and solar energy systems in desert areas
  - Environmental monitoring – cheap, large-scale deployment of sensors
  - Emergency management

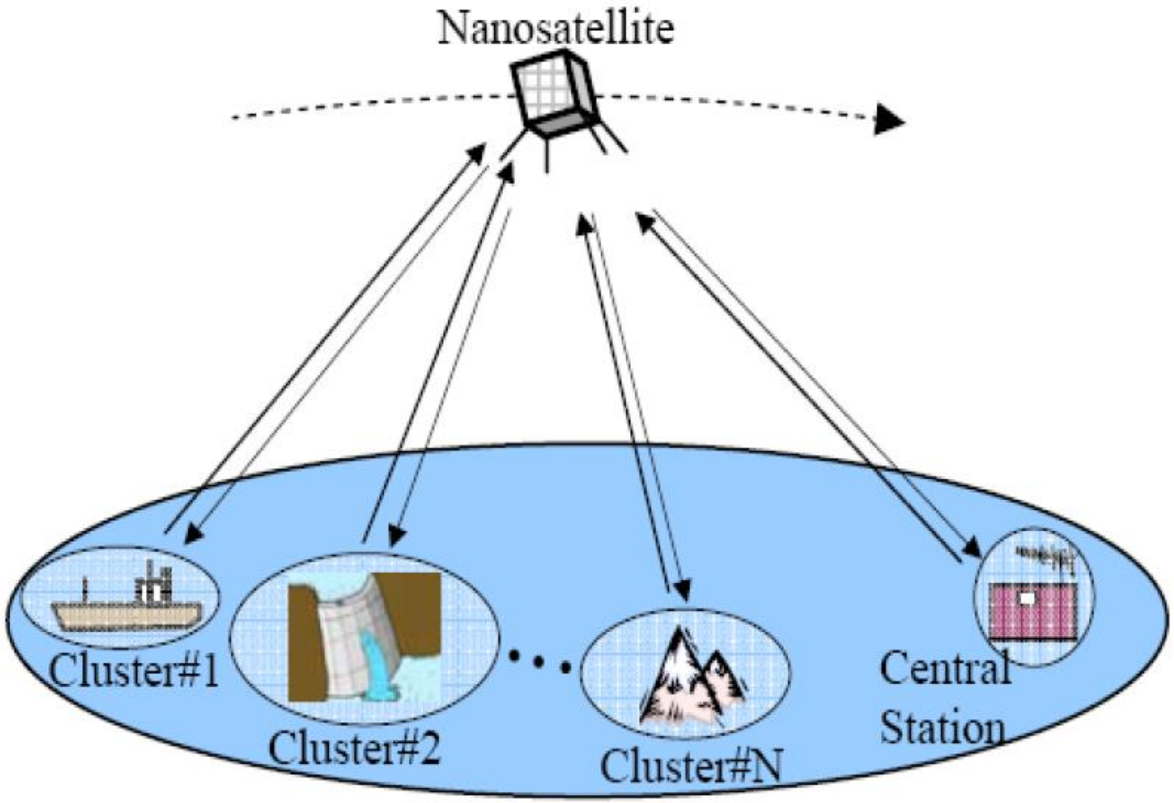


Example of a satellite system communicating with sensors and actuators.

[9] http://iot.ieee.org/newsletter/march-2016/the-internet-of-space-ios-a-future-backbone-for-the-internet-of-things.html
[10] E. Cianca, I. Bisio, et. al., "Satellite Communications Supporting Internet of Remote Things", IEEE Internet of Things Journal, Vol. 3, No. 1, February 2015.

Nanosatellite-linked Wireless Sensor Networks

- Nanosatellites, being relatively much cheaper, can be integrated as a component of wireless sensor networks [11]
  - sensor nodes =>
  - relay nodes =>
  - nanosatellite



WSN using store and forward nanosatellite

Source: [11]

[11] A. Addaim, A. Kherras and Z. Gennoun., "Design of WSN with Relay Nodes Connected Directly with a LEO Nanosatellite", Int. J. of Computer and Communications Engingeering, Vol. 3, No. 5, September 2014.

Data Mules: Routing in Cube/Nano/Picosat Constellation

- Tiny low power radios have very slow data rates (typ. 1 W, 1200 bps)
- Quantity of data and the transfer time can improved by a communication protocol that allows a sparse network of pico-satellite to transfer data directly between one another [12].
  - Routing algorithm considering satellite orbital movement to determine best path

Source: http://spacenews.com/news-from-the-itu-symposium-on-small-satellite-regulation/

[12] T. Koritza and J.M. Bellardo, "Increasing cubesat downlink capacity with store-and-forward routing and data mules"

CONCLUSION

- There is an increasing interest to utilize nanosatellites such as cubesats for satellite S&F based remote data collection systems.
  - Nanosatellites can play a vital role in connecting sensors widely dispersed on the ground, especially in remote areas.
  - Nanosatellites can play significant role in the concept of "Internet of Remote Things" and in the satellite-linked wireless sensor networks.

- Although low-cost, nanosatellite S&F systems will consist of simple communication payload with limited transmit power (tight link budget), computational and communication capabilities.

CONCLUSION

- To deal with technical constraints that impact system performance, especially low data rate, as well as the limited communication time, recent studies in literature investigate appropriate communication protocols and system optimization, albeit limited in theory and simulations.
  - Lack of practical engineering insights derived from actual systems

- The BIRDS-2 S&F mission comes into the picture by implementing an experimental proof-of-concept system consisting a cubesat constellation S&F system, and investigating the actual system performance and technical challenges.