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

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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]

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](http://www.qsl.net/kd2bd/kd2bd.html)

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Launch date</th>
<th>Communications Payload</th>
<th>Uplink</th>
<th>downlink</th>
</tr>
</thead>
<tbody>
<tr>
<td>UoSAT-2</td>
<td>1984</td>
<td>First store and forward mission 1200 baud AFSK 128 byte memory</td>
<td>VHF</td>
<td>VHF/ UHF</td>
</tr>
<tr>
<td>UoSAT-3</td>
<td>1990 (1)</td>
<td>Store and Forward 4 Mbyte filestore 9600 baud FSK digitally filtered HealthNet/VITA</td>
<td>VHF</td>
<td>Amateur Service</td>
</tr>
<tr>
<td>UoSAT-5</td>
<td>1991</td>
<td>Store and Forward 13 Mbyte filestore 9600 baud FSK digitally filtered</td>
<td>VHF</td>
<td>UHF</td>
</tr>
<tr>
<td>S-80/T</td>
<td>1992 (2)</td>
<td>Store and Forward 16 Mbytes filestore 9600 baud FSK digitally filtered</td>
<td>VHF</td>
<td>Amateur Service</td>
</tr>
<tr>
<td></td>
<td></td>
<td>transparent measurement transponder*</td>
<td>Amateur Service</td>
<td>Amateur Service</td>
</tr>
<tr>
<td>KITSAT-1</td>
<td>1992</td>
<td>Store and Forward 16 Mbyte filestore 9600 baud FSK digitally filtered</td>
<td>VHF</td>
<td>UHF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DSP experiment using TMS320C25/C30 provides capability for adaptive modulation</td>
<td>Amateur Service</td>
<td>Amateur Service</td>
</tr>
<tr>
<td>PoSAT-1</td>
<td>1993</td>
<td>Store and Forward 16 Mbyte filestore 9600/38400 baud FSK digitally filtered</td>
<td>VHF</td>
<td>UHF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DSP experiment includes MSK downlink option and adaptive modulation capability</td>
<td>Experimental</td>
<td>Experimental</td>
</tr>
<tr>
<td>KITSAT-B</td>
<td>1993</td>
<td>Store and Forward 16 Mbyte filestore 9600 baud FSK digitally filtered</td>
<td>VHF</td>
<td>UHF</td>
</tr>
<tr>
<td>HEALTHSAT-2</td>
<td>(3) 1993</td>
<td>Store and forward 3 x 16 Mbyte filestore 9600/38400 baud FSK digitally filtered</td>
<td>VHF</td>
<td>UHF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(WARC-92) Adaptive transmit power under on board computer control</td>
<td>(WARC-92)</td>
<td>(WARC-92)</td>
</tr>
<tr>
<td>For launch 1995</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CERISE</td>
<td>1995</td>
<td>9k6/38k4 baud Store and Forward 9k6-76k8 baud FSK DSP communications payload</td>
<td>VHF/</td>
<td>UHF</td>
</tr>
<tr>
<td>FaSAT-Alfa</td>
<td>1995</td>
<td></td>
<td>VHF/</td>
<td>UHF</td>
</tr>
</tbody>
</table>

Fig. 2. Experimental and amateur S&F satellites in 1980s and 1990s (Source: [3])

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.


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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/](http://www.vizocomsat.com/blog/importance-vsat-satellite-services-telemedicine/))

## Data Requirements of Various Services

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

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**

- **Sina-1** [5] (launched 2005, Iran, **160 kg**, 682 km x 704 km)
- **ANUSAT** [6] (launched 2009, ISRO & ANU, India, **38 kg**, 550 km)
- **WAPOSAT** [7] (launched after 2012, UNI and WAPOSAT company, Peru, **<5 kg, 2U** cubesat constellation, 1000 km)


**Trending: From Micro- to Nanosatellite S&F Systems**

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

Source: [8]

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


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

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.

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

Iruzu 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])

Irazu Project

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

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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.
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)

Enhanced Water Level Station

- Solar Panels
- Rain Gauge
- arQ Datalogger
- Satellite Antenna
- External Power Pack
- Water Level Sensor
- Camera

Courtesy of Joven Javier, DOST ASTI
Automated weather stations are deployed in strategic locations such as rivers and other bodies of water.
### 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

| 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 |
| 12. | arQ temperature |
| 13. | arQ Humidity |
| 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

<table>
<thead>
<tr>
<th>Byte #</th>
<th>Other fields</th>
<th>Information Field</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2-8</td>
</tr>
<tr>
<td>Content</td>
<td>Start flag</td>
<td>Satellite callsign</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Byte #</th>
<th>Other fields</th>
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</thead>
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<tr>
<td></td>
<td>1</td>
<td>2-8</td>
</tr>
<tr>
<td>Content</td>
<td>Start flag</td>
<td>Ground terminal ID</td>
</tr>
</tbody>
</table>

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)

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

\[ \tau = 400 \text{ km/c} + 144 \times 8 \text{ b/(1200 b/s)} + 250 \text{ ms} = 1.21 \text{ s} \]

- 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
  \[ N_{slots} = \frac{180s}{1.21s} = 148 \text{ slots} \]

- 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, \( \frac{24}{0.5} = 48 \text{ packets/day/GST} \)
  - Divided by 3 satellites with 2 passes each/day, \( \frac{48}{6} = 8 \text{ packets/GST/pass} \)
Communication Scenario (Sample Case)

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

\[ N_{GST} = \frac{118}{8} = 15 \text{ GST/location} \]

- 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

"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.”

The Internet of Things

Source: [X]

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.

Nanosatellites, being relatively much cheaper, can be integrated as a component of wireless sensor networks [11]

- sensor nodes =>
- relay nodes =>
- nanosatellite

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


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.
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.