RILDOS: A Beaconing Standard for Small Satellite Identification and Situational Awareness

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ABSTRACT

The increasing launch pace of small satellites and CubeSats presents a growing challenge to identify and locate newly launched satellites. This impacts mission success primarily through the inability to consistently perform rapid and accurate determination of satellite identity and orbital location after deployment. This paper proposes an approach to resolve this issue through a simple radio and message broadcast standard providing definitive identification, location, and operational state data on a low power, very low data rate subcarrier. Called RILDOS (Radio with Identity and Location Data for Operations and SSA [Space Situational Awareness]), this would be an open standard available for use in new systems. RILDOS is a repeating, unencrypted message broadcast with a unique identifier, timestamp, spacecraft derived position / velocity / acceleration, and predefined emergency flags. The spread spectrum signal is transmitted at a low power and very low data rate and can be radiated continuously or only while in contact. Centering the signal underneath the primary radio frequency for the satellite avoids the need for additional frequency deconfliction or a secondary radio. Cycling every ten seconds, a short collection gathers enough data for an orbital determination as well as top level status about the health of the satellite.

INTRODUCTION

With the satellite industry launching increasingly large numbers of small satellites, the challenges in performing space operations have increased and with those challenges come increased risks for mission failure. A key risk encountered is the inability to precisely locate a specific satellite in a cluster of newly deployed small satellites. Following that, there remains a growing risk from unplanned and unanticipated orbital conjunctions due to the proliferation of new satellites in crowded orbits.

Currently, some of the solution for this is provided through the voluntary actions and data publication of the satellite owners and operators. This is not real time data and access to it can be haphazard, as the data transfer is usually point-to-point personal networking. Another partial solution is the availability of space catalog data from the United States Air Force's Joint Space Operations Center (JSpOC), which collects and compiles space tracking data from the Space Surveillance Network.

Neither of these solutions fully solves the challenges for space operations. Timeliness of data, accuracy, and completeness of data is not guaranteed in either case. A solution that utilizes the satellite itself as the origination point for the critical data, broadcast from the satellite to all interested parties to acquire and use as needed is the best model. This model addresses what is essentially a requirement for an M:N multicast system, where the M satellites each transmit their data for all N concerned parties to monitor and make their own determination how to best use that data.

Given the competing multi-national and commercial interests represented by the satellite industry, a consolidated industry-wide solution imposed by regulatory agencies to ensure universal space object tracking and identification is unlikely to occur. Yet, the need for a capability to meet this challenge is required. One solution that has worked well in the past is the development of an open standard that is managed by a community consortium, where any independent hardware or software vendor can implement the standard in their products. Two examples of this in the small satellite community are excellent analogs: the CubeSat standard and the P-POD standard.

Presented within this paper is a starting point for a proposed open standard, industry and community driven solution. Called Radio with Identity and Location Data for Operations and SSA [Space Situational Awareness], or RILDOS, this solution implements an open radio signal standard that broadcasts vital satellite identity and orbital data to any party which locks on and uses a modem that demodulates the signal. Using a very low data rate – 50 bits per second (bps) – unencrypted data frame modulated on top of a spread spectrum, Gold Code based signal enables the message to be transmitted at a low power at the center frequency of the primary satellite downlink, even as the primary downlink is active. Using this approach, which is similar to the "below the noise floor" approach of a GPS signal, simplifies the overall spacecraft design and complexity, while making the signal easy to find and demodulate for ground users.

The radio standard proposed encompasses the data format of the signal, with detailed definitions of each data item and how they are to be interpreted, as well as the Radio Frequency (RF) and modulation information. Provided with the standard, a vendor could develop either a spacecraft radio that transmits the signal or a modem that receives and delivers the data. Care has been given to engineer the standard to minimize spacecraft power impacts, implementation cost and complexity, limit any compromise of the primary RF link design, and to maximize operational potential.

This paper provides background on the standard, and serves as an introduction to the community for this concept. To do so, a description of the problem this standard addresses is provided. Following that, the standard is described, not only from a data content and rationale point of view, but also by a discussion of the waveform and encoding of the signal. That discussion also covers how the placement and power of the RILDOS signal will impact the primary downlink. Next, how the RILDOS standard would be implemented for both the space transmitter and the ground receiver is illustrated. The steps presented are intended to show the basic actions to implement the RILDOS signal, but are not intended to restrict a vendor from providing innovative designs, so long as the same transmission and data standard is used. In order to highlight the benefits of RILDOS enabled satellites, concepts of operations (CONOPS) are provided for the owner-operator, neighborhood operators, and overall Space Situational Awareness (SSA) programs. This enables a starting point for discussions of new capabilities or uses. Finally, a path forward is proposed, laying out next steps and inviting the small satellite community to refine and implement the RILDOS standard.

PROBLEM AND BACKGROUND

For many decades, upon launch a booster would deploy a primary payload and perhaps one or two secondary payloads. The timing of each deployment was well understood and the post deployment behavior varied between payloads. The small number of objects to track and communicate with post deployment, coupled with their fairly easy to identify characteristics ensured that there was little confusion by their respective operators post deployment. This meant that contacts could quickly occur and mission activities, especially in the critical first few contacts, could be accomplished.

However, the rapid growth of the small satellite community, and in particular the ability to launch large numbers of cubesats and deploy them near simultaneously has made the older techniques and tools for performing discrimination of each object far less effective. Now instead of a couple of secondary payloads, there may be dozens. To compound the problem, they may be deployed in clusters, such as what happens when three 1U CubeSats are ejected by a single P-POD, or when several P-PODs deploy their loads within a span of a few minutes. Adding to the confusion, the behavior characteristics could be very similar for some of them, especially if they do not have a propulsion system. Another issue hindering the identification and tracking of the satellites in a cluster is the potential lack of radio frequency deconfliction, so that several satellites may be on the same or overlapping center frequencies. The net result of these conditions is that there is a cluster of a few to a few dozen poorly identified small satellites in similar orbits.

The United States Air Force's Space Surveillance Network does track these newly deployed satellites, attempting to clearly tie a single catalog object with a consistent track and orbit. That however, is a far from perfect solution. It may take several days of tracking to clearly define each object, during which time the tracks (and thus predicted ground antenna angles for contacts) can change.

This directly translates into mission impacting problems for satellite operators. First, the initial contacts with a newly launched satellite are among the most critical for any mission, and generally are well rehearsed and planned. These contacts are the immediate opportunity to verify that the spacecraft is operating as planned and in a safe mode. If these contacts are missed, and the spacecraft is in an anomalous state, the mission may end if the spacecraft dies, or the objectives of the mission may be curtailed if the spacecraft is damaged. Having poor or essentially no detailed knowledge of the satellite orbit will lead to multiple attempts and multiple failures for these first contacts, wasting vital time in a risky portion of the mission profile.

Another challenge is longer term. The proliferation of small satellites makes orbital conjunctions more likely. Even though the spacecraft is identified and tracked by the Space Surveillance Network, it may only get its orbital elements updated every few days, and the amount of error in these updates and the propagation of the elements may be very significant. For satellite operators whose satellites are in intersecting orbits, or in co-planar orbits, reliance upon the orbital elements published is generally the only option. They can reach out to network with some of the other satellite operators, but that can be a lengthy and unreliable approach to gathering data regarding the other satellite's position. Additionally, unless a near real time data feed is established, the periodicity of that networking and data exchange may be unpredictable and not timely enough for making operational decision.

Both these scenarios have at their heart the same core problem: How can a satellite in orbit be easily identified with clear, accurate orbital data? Although partial solutions to this problem exist – such as use of the data from the Space Surveillance Network – none provide timely, unambiguous data to all interested parties in a direct and reliable manner.

The most direct solution to this problem is similar to those adopted by ships or airplanes, where the vessel in question has a beacon continuously broadcasting with its identity and position. However a major difference between the small satellite community and the aircraft or maritime community is the lack of a single coherent international standards organization that has authority to mandate a single format and signal for use. Another difference is the power available to broadcast the signal. Unlike airplanes or large motor vessels, a small satellite has a delicate electrical power balance and every watt is tightly budgeted and planned. The same condition applies for mass and size, where unlike a modern airliner or ship that can easily accommodate a 5 or 10 kilogram box with 1000 cm^3 volume being placed in it, a smallsat may have just a fraction of a percentage of that volume or mass available for use, if at all. Finally, the wide array of frequencies used by different spacecraft for just as wide a variety of reasons has to be accommodated. There is no one size fits all frequency for spacecraft, and attempting to specify a single, dedicated frequency will result in dedicated radios having to be added to each spacecraft for this beacon.

Even within this tight set of constraints, there is still room for a solution. Using a standardized data format and placing the beacon signal on a spread spectrum carrier broadcast many decibels below the main carrier for each satellite offers a direct and low cost solution. The RILDOS standard proposes to instantiate that approach, and to provide an open standard for the community as a whole to use and implement, free of proprietary lock in and licensing fees.

RILDOS STANDARD

Given the context of the problem as described, the RILDOS standard is targeted to directly address the parameters that will provide the maximum value in the solution. This includes defining the data content of the message to enable adequate location and identity information while enabling future growth of the standard and also flexibility for operators to define unique capabilities they wish to utilize with the message. Another dimension addressed in the standard is the waveform and encoding. Even more than with message data content, the waveform and encoding must enable a wide variety of link budgets to implement the standard, which requires analysis of several potential use cases and then development of the waveform and encoding to provide guidelines that will not perturb the most fragile of these link budgets. Finally, the standard also defines how the signal is processed upon receipt. This closes the link and provides the final information for a team of spacecraft and ground system developers to implement the RILDOS standard for their mission.

Data Content

The definition of the message data content for the RILDOS standard is critically important, as this definition must be precise and allow clear identification and location of the transmitting satellite. The transmitting satellite identity is vitally important, and while other aspects of the standard assist in its identification, the definitively attributable identity information is contained in the message itself. Once identified, the location of the satellite is also critical. As the satellites using RILDOS may be in a variety of orbits – both Geocentric and Heliocentric – in order to best serve the space operations community the RILDOS standard must service both orbit regimes. Once identified and located, the message continues to provide unique information that benefits RILDOS users. First, a byte of standardized satellite health flags is defined. This permits quickly alerting for satellite problems and state of health. Next, there is a section of data reserved for future RILDOS use. Later definitions of the RILDOS standard may add new data fields that the community had determined provide broader benefits for satellite operators. Finally, there is a section in the message that is reserved for satellite operators to use as they determine is useful to their concept operations and mission requirements. Starting with an overview discussion of the message, each section of the message is then described in detail, with each field and the rationale for the formatting and inclusion highlighted.

The RILDOS message is a 500 bit long, single page format that is broadcast unencrypted at a 50 bits per second (bps) data rate. As such, it takes ten seconds to collect the full page message. The bit rate is a function of the waveform and encoding requirements discussed later in the paper for optimizing the power requirements of the signal, but the use of a low data rate is not unprecedented, as the GPS L1 and L2 signals use a 50 bps data rate as well.[1] The message size was determined and set to provide a short enough time to allow quick collection if many messages from different satellites need to be collected near simultaneously, but also such that the message would have sufficient room for all the required data as well as room for later growth. The choice of 500 bits length provided that room for required data and expansion while allowing a frequent enough page repeat rate. With a ten second duration, six messages per minute can be collected, which from an orbit determination perspective means that there is enough data to attempt to smooth the position data and use that as a seed for ephemeris propagation. In terms of update of the health flags included in the message date, the ten second duration balances the frequency required to keep the health flags fresh versus the additional loading on the system to generate the data and send it to the radio for inclusion in the message frame.

Keeping the RILDOS data transmission unencrypted is a key aspect of the standard. This permits the entire space operations community to receive the RILDOS signal from any satellite, and thus gain critical identity and location information that may be required for awareness of other nearby satellites. More broadly, the unencrypted signal fosters broad space situational awareness and tracking, which has been a challenge for all parties and is a problem increasing in complexity and urgency with the success of the small satellite community.

The message content starts with a header section. (Note that the detailed breakdown of the message content is shown in Figure 1.) The first item in the header is a synchronization code. A single pattern is proscribed, so that frame synchronization at the start of each page is standardized and easy for all potential users who wish to receive RILDOS signals. A 24 bit pattern is sufficient to provide the unambiguous lock for the start of the page. The next field is the Satellite Vehicle Number (SVN). This is set by the operator prior to launch to provide a clear tie from the satellite transmitting the signal to the owner and operator. Once set it is not changed. The values range from 0 to 16,777,215 as integers, allowing for an immense number of spacecraft. Deconfliction of the SVN numbers selected should be worked out prior to launch, and a centralized database of SVNs tied to operators would be of benefit to the community. The next item in the header is the RILDOS Standard Version descriptor. This is an integer that ranges from 0 to 255, where each new version of the standard increments the integer. Having the version as self-describing in the data frame permits the RILDOS standard to evolve over time even if older spacecraft do not update their broadcast message format. Next, a timestamp for the message frame is included. The time stamp is given to the millisecond level and is synchronized to the first bit of the message data frame, e.g., bit 0. For satellites with a GPS receiver, this timestamp should be GPS time. For those without GPS receivers, the spacecraft clock time from the on-board processor should be used. The final data field in the header is a two bit field that defines what coordinate system the position data uses. Two coordinate systems are used – ECI J2000 for Geocentric orbits and Heliocentric Earth Equatorial (HEEQ) for Heliocentric orbits. When this field is set to "00", the position data is given for Geocentric Orbits and when the field is set to "01", HEEQ data is used. The values "10" and "11" are reserved for future use.

The next portion of the message is the position data. For Geocentric orbits, the first data provided is a byte of data that provides simple navigation solution flags and GPS receiver status, if a GPS receiver is used to provide position data. The first two bits identify what GPS receiver the spacecraft is using (Either none "00" or 1 through 3 using bit settings "01" to 11"). The next two bits provide a status of the navigation solution. If it has no errors or other issues the bits are set to "00", and if it was rejected they are set to "11". Settings "01" and "10" are reserved for future RILDOS standard use. The remaining four bits in the byte are for the spacecraft operator to define flags for their own use that describe

RILDOS Message Content Structure (Version 1.0)

Item	Range	Units	Example	Start Bit	End Bit
Sync Code	0xBADCAB	--	0xBADCAB	0	23
SVN	0 to 16777215	--	1023	24	47
Standard Release	0 to 255	--	14	48	55
Timestamp	parse by field	Time	2012/366/23:59:60.999	56	99
Coordinate System	0 to 3	--	1	100	101

Item	Range	Units	Example	Start Bit	End Bit
GNSS Flags	00000000 to 11111111	--	10111101	102	107
x	` +/- 85899345.91	m	711572.99	108	144
y	` +/- 85899345.91	m	456852.99	145	181
z	` +/- 85899345.91	m	1254789.99	182	218
x dot	` +/- 10485.75	m/s	5245.99	219	242
y dot	` +/- 10485.75	m/s	7550.99	243	266
z dot	` +/- 10485.75	m/s	6548.99	267	290
x dot dot	` +/- 655.35	m/s^2	-11.99	291	309
y dot dot	` +/- 655.35	m/s^2	125.99	310	328
z dot dot	` +/- 655.35	m/s^2	325.01	329	347
	Total Bits (Geocentric)	***246***			

Item	Range	Units	Example	Start Bit	End Bit
Navigation Flags	000000000 to 111111111	--	101011000	102	110
x	` +/- 1407374883553.27	m	12234765876.23	111	162
y	` +/- 1407374883553.27	m	-40052765876.99	163	214
z	` +/- 1407374883553.27	m	32165498725.01	215	266
x dot	` +/- 41943.03	m/s	27550.99	267	293
y dot	` +/- 41943.03	m/s	-12568.01	294	320
z dot	` +/- 41943.03	m/s	32587.23	321	347
	Total Bits (Heliocentric)	***246***			

Item	Range	Units	Example	Start Bit	End Bit
Emergency Flags	00000000 to 11111111	--	11111111	348	355

For each flag, **0 = Nominal; 1 = Emergency;** Definitions: **Bit 348** - Loss of Attitude Control; **Bit 349** - Unable to Receive Commands; **Bit 350** - Power Subsystem Anomaly **Bit 351** - Propulsion Subsystem Anomaly; **Bit 352** - On Board Processor Anomaly; **Bit 353** - Thermal Anomaly; **Bit 354** - Payload Anomaly; **Bit 355** - Other Vehicle Anomaly

Health Flags

Item	Range	Units	Example	Start Bit	End Bit
Future Use Bits	0xA5A5A5A5A5A5A5A5	--	Repeating Hex "A5" as fill	356	419

Reserved for future RILDOS standard use. Definitions are TBD for future standard releases.
To be filled as pattern 0xA5A5A5A5A5A5A5A5

Item	Range	Units	Example	Start Bit	End Bit
Spacecraft Use Bits	All zeros to all ones	--	0x12AB34CD56EF	420	467

Reserved for spacecraft use. Definitions are determined by spacecraft and can be proprietary.
Returned as hex string from modem. Filled as pattern 0xA5A5A5A5A5A5 when not in use.

Item	Range	Units	Example	Start Bit	End Bit
Checksum	All zeros to all ones	--	0xFE98DC76	468	499

32 bit CRC Standard

Bit 0

Header Data
Bits: 0-101

Bit 101

Position Data
Bits: 102-347

Coordinate system bits in header determine format.

Use Geocentric if the bits for coordinate system = 00.

Use Heliocentric if the bits for coordinate system = "01"

Bit 347
Bit 355

Reserved
Bits: 356-419

Bit 419

S/C Use Data
Bits: 420-467

Bit 467

Checksum
Bits: 468-499

Bit 499

Figure 1: RILDOS Data Message Content

the quality or origin of the position data, such as if data is derived from star tracker algorithms. The X/Y/Z position data is defined with respect to the J2000 standard and given in meters. The fields permit large enough numbers, ranging +/- 85,899,345.91 meters, to use with highly eccentric orbits that have apogees greatly past geosynchronous orbit. Similarly, the velocity data is also provided in meters per second and ranges +/- 10,485.75 meters per second. This range is sufficient for LEO, GEO, and HEO orbital velocity. Finally, the X/Y/Z acceleration fields provide for a range of +/- 655.35 meters per second squared. In total, 246 bits are used for the Geocentric orbital data.

Fitting in the same 246 bits that the Geocentric orbital data uses, the Heliocentric orbital data provides navigation flags, X/Y/Z position and velocity data for deep space missions. As with the Geocentric data, the position data is in meters and the velocity data is in meters per second. As deep space navigation is significantly different than Earth orbit navigation, no acceleration data is provided. There are nine bits allocated for spacecraft navigation flags, whose definition is to be decided upon by the spacecraft operator. Following that, the position data is provided using a HEEQ coordinate system, with each position point having a range of +/- 1,407,374,883,553.27 meters. In theory, this provides for spacecraft that may have orbital apogees that are approximately 10% past Jupiter. The velocity field also has a far greater range than Geocentric orbits, again reflecting the nature of interplanetary missions. In this case, the velocity field has a range of +/- 41,943.03 meters per second.

Once past the 246 bits of orbital data, the next section of the message is a single byte of pre-defined state of health flags. These are used to signal any spacecraft anomalies that may need attention from the ground system. They are defined only in general terms. As example, the third bit in the byte (and bit 350 in the overall message frame) is for Electrical Power Subsystem anomalies. When set to "0", conditional is nominal, and when set to "1", the flag indicates that there is an emergency within the Electrical Power Subsystem. It is up to the spacecraft operator to set the conditions for each flag to alarm. The inclusion of these flags in the message allows for some level of "neighborhood watch" or shared alarming under CONOPS where the vehicle continuously transmits the low power RILDOS signal at all times.

The next portion of the message frame is an eight byte reserved portion. This section is reserved for future RILDOS standard use and shall be set to a repeating hexadecimal pattern of "A5" until further defined by the RILDOS standard.

Following the RILDOS reserved portion is a six byte section that is open for the spacecraft operator to define as they choose. They may use this portion to define and broadcast proprietary data flags, and can even define a frame counter within it to subcommutate the section, thus providing more unique data bits for their use. As an example, a user who takes four bits as a counter would have 44 bits remaining for data. Across the sixteen pages arising from that four bit counter, 704 unique bits can be defined that would take two minutes and forty seconds to be downlinked. When not used, this section should be filled with a repeating hexadecimal pattern of "A5".

The final portion of the message frame is a 32 bit Cyclical Redundancy Check (CRC), calculated and inserted by the spacecraft. The CRC used is a straightforward implementation of the 32 bit CRC algorithm developed at Rome Labs in the 1970s.[2]

As previously discussed, the message data format is designed to provide maximum operational benefit under a number of significant constraints, where the low data rate mandated by the need to keep the signal at the minimum acceptable broadcast power is the driving requirement. Within that bound however, there is still room for enough descriptive data that clearly identifies the spacecraft and its orbit as well as some emergency state of health data. Additionally, the message format also provides room for future growth with data fields available for the spacecraft operator to define. In all, this unencrypted data format serves the purpose intended and when encoded upon the RILDOS waveform, it forms the basis of a messaging system that directly addresses the space situational awareness problems currently facing the small satellite community.

Waveform and Encoding

This section describes the RF and signal processing characteristics of the RILDOS signal. The RILDOS signal uses spread-spectrum modulation with a very high spreading frequency versus information data rate. This allows it to be transmitted at a very low relative power versus telemetry downlink. Since the power is very low relative to the telemetry signal, it can be transmitted in the same band as the telemetry signal, thus saving bandwidth. The specifics of the waveform processing and modulation are described in detail in the following paragraphs.

The RILDOS signal is a 50bps, Bi-Phase Shift Key (BPSK) modulated, Direct-Sequence Spread-Spectrum (DSSS) waveform. This means that the RILDOS message sequence is transmitted at the rate of 50bps. This transmitted data sequence is exclusive-OR'd with a spreading data sequence which is defined to be 1Mega Chips Per Second (Mcps). A spreading bit is traditionally termed as a Chip. This leads to the definition of Chips-per-Second or cps rather than typical bit-per-second or bps which are reserved for the information or message data. The notional implementation is illustrated in Figure 2.

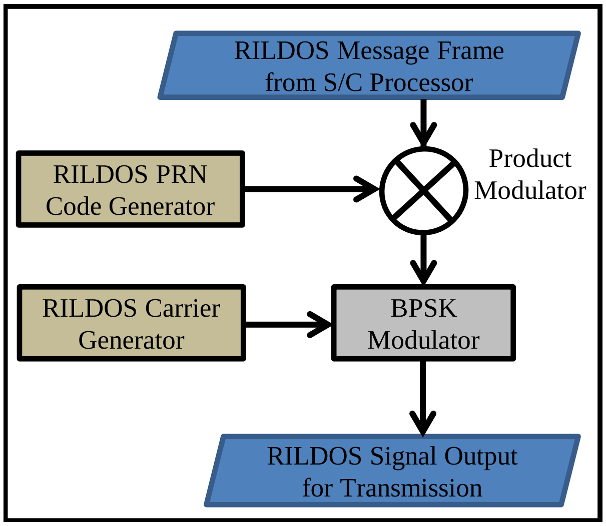


Figure 2: RILDOS Signal Generator

The RILDOS signal is co-located at the same center frequency as the spacecraft's telemetry downlink signal. It can be transmitted with significantly less power than the telemetry signal due to the processing gain realized by the spread-spectrum de-correlation process. This waveform standard borrows concepts extensively from the proven standards of the GPS links. [1]

An example spacecraft telemetry downlink with the RILDOS waveform transmitted simultaneously is illustrated in Figure 3. The relative power levels of the two signals are normalized for illustrative comparison purposes. In actuality, the RILDOS signal is transmitted with significantly lower relative power.

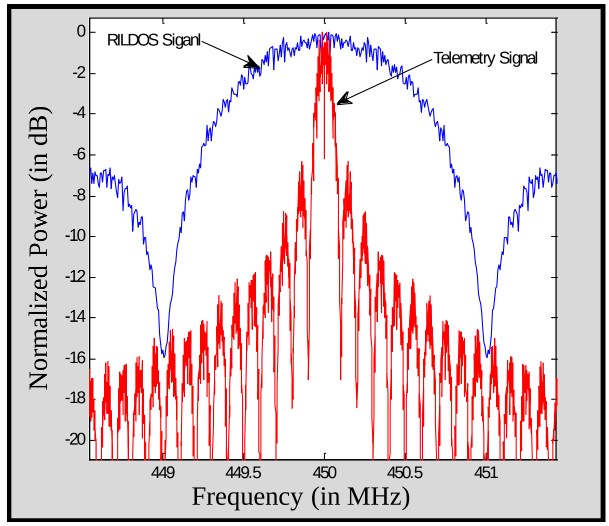


Figure 3: Spacecraft Downlink Telemetry Waveform with RILDOS Waveform Compared Using Same Power

DS Spreading

The DS Spread-Spectrum standard is defined as the exclusive-OR of the information data (50bps information sequence) with the much faster Spreading PN data sequence (1Mcps). The RILDOS spread-spectrum processing requires that the spreading chips and the RILDOS data bits are synchronous. More specifically, this specifies that the data transition of an information bit aligns with the data transition of spreading chip. This significantly eases the de-spreading and bit-synchronization tasks for the receiving equipment, thus eliminating unnecessary complications.

Chip Rate and Processing Gain

The chip rate is specified to be exactly 1Mcps. This rate is chosen to ensure that the resulting spread-spectrum waveform does not exceed the bandwidth restrictions of typical UHF channel allocation of 5MHz of allocated spectrum. Specifically, the 1Mcps spreading rate produces a Null-to-Null Bandwidth of 2MHz. In order to meet spectral-mask requirements, signals must often be pulse-shaped in order to minimize or eliminate the power in the sidelobes. However, since the RILDOS signal is transmitted with little power relative to the telemetry signal and the second sidelobes, which are at the 5MHz UHF bandwidth channel edges, are an additional 10dB down, no pulse-shaping of the RILDOS signal is required. This is illustrated in Figure 4, which shows the RILDOS Spectrum Utilization.

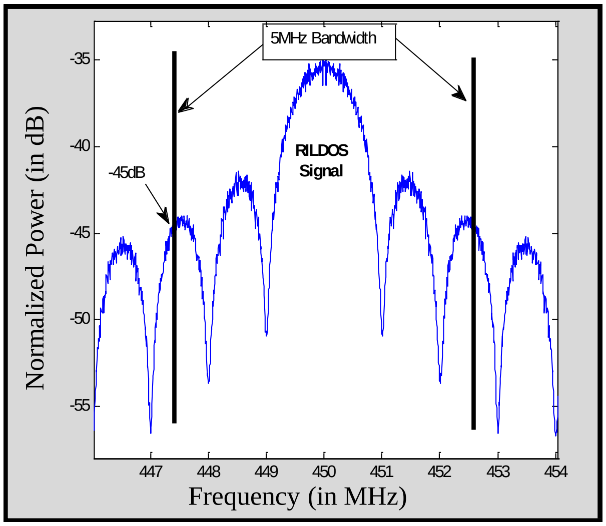


Figure 4: RILDOS Spectrum Utilization

Processing gain is a figure-of-merit for spread-spectrum signals and is defined as the peak power increase in the spreading signal after the receipt processing de-correlation operation. Effectively, this means that the spread-spectrum signal "rises out of the noise floor" after receive processing. The Processing Gain is calculated by comparing the relative bit rates of the information data stream and the spreading data stream. Given a data content bit rate of 50bps, this yields a spread-spectrum processing gain for the received waveform of 43dB. The processing gain is calculated for a direct-sequence spread signal using Phase Shift Key (PSK) modulation by taking the ratio of the chipping rate to the modulated symbol rate. The equation illustrating this is shown below in Equation 1.[3]

$$\textit{Processing Gain} = 10 * \log_{10} (\boldsymbol{C_r}/\boldsymbol{B_r}) \quad (1)$$

$$\textit{Processing Gain} = 10 * \log_{10} (1000000/50)$$

$$\textit{Processing Gain} = 43 \text{ dB}$$

Where $\boldsymbol{C_r}$ *is the Chipping rate of the RILDOS Standard and* $\boldsymbol{B_r}$ *is information data rate of the RILDOS Standard*

The use of a Spread-Spectrum signal with such a large processing gain has 3 simultaneous benefits for the RILDOS signal. First, upon de-spreading the signal, the BPSK-modulated RILDOS waveform will increase in amplitude by 43dB. Simultaneously, the telemetry waveform will reduce in amplitude by the ratio of the telemetry signal's symbol rate to the chipping rate. Finally, the telemetry signal can still be processed by a separate receiver dedicated to the telemetry signal without a measurable impact on BER since the RILDOS waveform is so low in power relative to the telemetry signal. This dedicated receiver does not de-spread the waveform but simply processes the telemetry signal and treats the RILDOS signal as uncorrelated noise. Since the spread RILDOS signal is greater than 28dB below the telemetry signal it does not affect the telemetry receiver's processing.

Required RILDOS Transmit Power

This section describes the power required to be transmitted for the RILDOS signal. This power is represented in dB relative to the power of the telemetry signal. By expressing the power relative to the telemetry signal's power, the user can use their pre-developed Telemetry link budget for their telemetry signal and simply scale the transmitted RILDOS power appropriately.

Due to the large Spread Spectrum processing gain of 43dB (as calculated earlier), the RILDOS waveform can be transmitted with significantly less power than the primary spacecraft telemetry signal. The received Eb/No required for the RILDOS waveform is 15dB. Based on Shannon's Information Theory Capacity Curve, this ensures error free reception of the navigation data within the RILDOS frame without the use of any forward-error-correction methods.[4]

Therefore to ensure an Eb/No for the RILDOS signal of 15dB given a spread-spectrum processing gain of 43dB, while eliminating interference to the primary telemetry signal, the RILDOS signal must be transmitted with a power of not greater than -28dB relative to the telemetry waveform. This is illustrated in Figure 5 which shows the relative transmitted power of the RILDOS signal and the telemetry signal. Notice that the RILDOS signal is approximately -28dB below the power of the Telemetry signal. Transmitting with a smaller relative power gap will not impact the RILDOS signal, but may result in unnecessary interference or degradation of the primary telemetry signal.

An example is shown below which describes both the calculations as well as the signal processing performance for the RILDOS signal. This example uses a notional telemetry signal of 100kbps with R=1/2 Viterbi decoding. The example can be extrapolated to the user's actual telemetry signal specifications.

Assumption: Telemetry Signal is 100kbps, BPSK modulated, R=1/2 Viterbi Encoding

- Symbol Rate of telemetry signal: **200ksps** (100kbps * 2 for Convolutional Encoding).
- Symbol Rate of Spreading Signal: **1Mcps** (specified by RILDOS Standard)

- Ratio of spread to telemetry symbol rates waveform: **5** (1Mcps/200ksps)
- Processing Loss due to spreading de-correlation by the Receiver: 10* $\log_{10}(5)$ = **7dB**. (This is the reduction in peak signal power that happens to the telemetry signal when it is de-spread by the RILDOS receiver.)
- Required Eb/No of de-spread RILDOS waveform: **15dB** (Derived from BPSK BER theory curve)
- Processing gain due to spreading de-correlation by the Receiver: **43dB**
- Therefore, the RILDOS waveform for this notional case can be transmitted at: 7dB + 43dB – 15dB = **35dB** below the power of the telemetry waveform.

This example highlights how the symbol rate of the primary telemetry signal can influence the required relative transmission power for the RILDOS signal. The “slow” rate of 200ksps for the primary telemetry signal in this example allows a RILDOS signal to be transmitted at a lower relative power than the worst case scenario of -28 dB, in this case -35dB. The figures below illustrate the relative power difference between the main telemetry signal and the RILDOS signal, and how the signals interact. The first figure (Figure 5) shows the relative powers of the telemetry signal and the RILDOS signal.

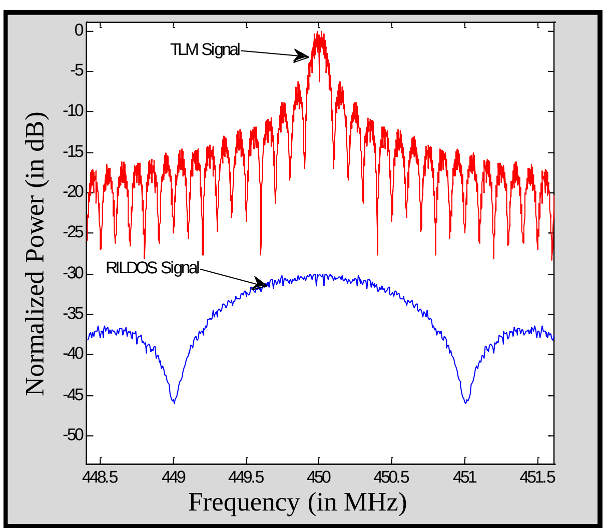


Figure 5: RILDOS & Telemetry Signals Prior to RF Summing Showing Relative Power Levels

Figure 6 illustrates the RF sum of both waveforms, illustrating the composite waveform the satellite actually transmits. As shown, the RILDOS signal has little effect on the telemetry signal. The telemetry signal can thus be processed by a standard telemetry receiver.

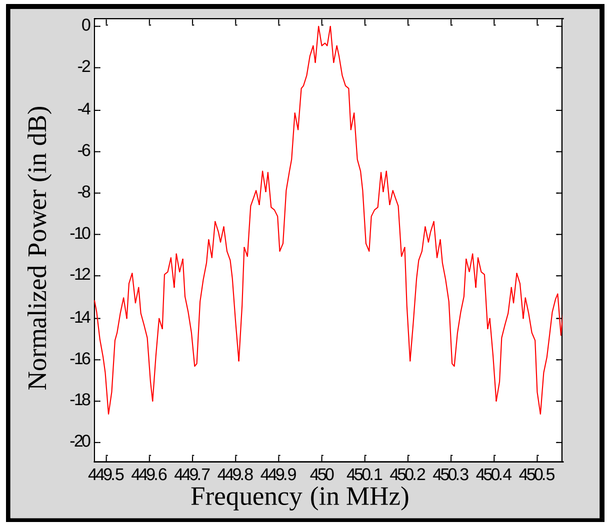


Figure 6: Composite Satellite Downlink Waveform (RILDOS + Telemetry Signals)

The composite signal is also passed to a RILDOS spread-spectrum receiver. After Spread-Receiver de-correlation, the resulting spectrum is illustrated by Figure 7. This resulting spectrum shows a RILDOS BPSK signal which is 15dB above the associated noise floor. The noise floor is developed by the spreading of the telemetry signal. The BPSK signal is then processed using a standard BPSK receiver and the frame information is derived.

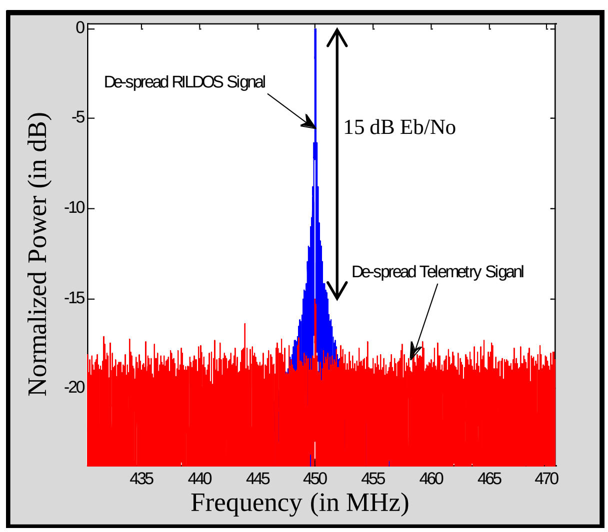


Figure 7: RILDOS Signal after Receiver Decorrelation

A generic equation for the required relative transmitted power for RILDOS signal (as compared to the Telemetry signal) is defined below:

$$\boldsymbol{Tx_{power}}\,[\text{db}] = 10 * \log_{10}(\boldsymbol{C_r}/\boldsymbol{T_r}) + 43 - 15 \qquad (2)$$

Where $\boldsymbol{Tx_{power}}$ is the required relative (wrt below the main telemetry signal) power for the RILDOS signal; $\boldsymbol{C_r}$ is the Chipping rate of the RILDOS Standard; and $\boldsymbol{T_r}$ is primary carrier's telemetry symbol rate

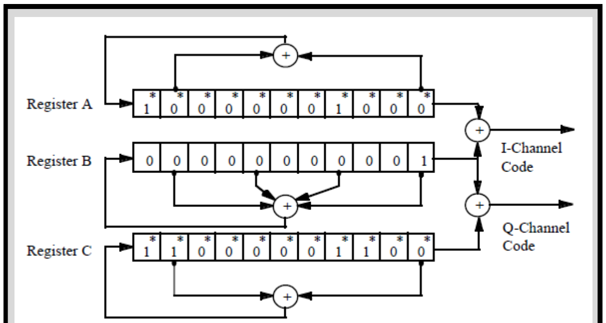
DS Spreading Code

The spread spectrum PN spreading code uses a standard Gold-code. They are specified by the NASA 451-PN CODE-SNIP code book.[5] The selected code is the Return Mode 2 short code. This code is well characterized and relatively short in length. This allows for both ease of generation and ease of de-correlation.

The code is 2047-bits in length, repeating every 2047 microseconds. Since the code repeats very quickly, acquisition of the code within a few seconds is expected for any receiver implementation.

There are approximately 400+ unique codes for this family of gold-codes. This allows for code deconfliction and separation within a cluster of satellites and significantly mitigates the chances of code overlap during orbital conjunctions

Figure 8 below shows the generator for the PN code and is from the NASA 451-PN CODE-SNIP code book. The NASA document explicitly describes the code and initial conditions in detail.



PRN Code Generation

(Figure Source: <u>*Space Network Interoperable PN Code Libraries (451-PN CODE-SNIP)*</u>*, Rev 1, NASA Code 451 GSFC, November 1998, Figure 2-3*)

Figure 8: Spreading PN Data Sequence Generator

Receipt Processing

The processing of the RILDOS signal is very similar to that of a standard GPS receiver. A block diagram of this processing is shown in Figure 9.

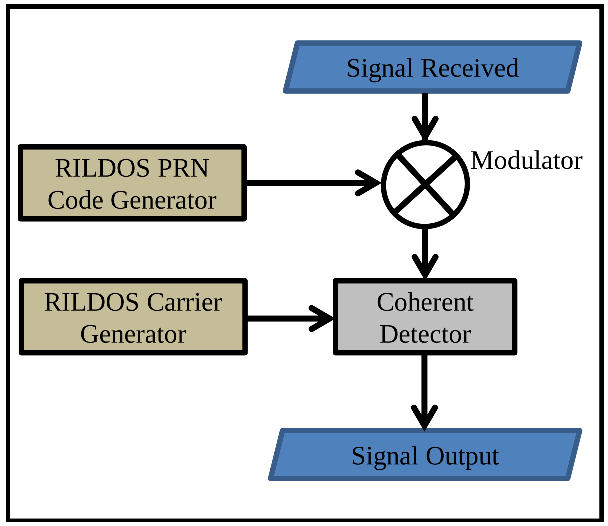


Figure 9: General Spread Spectrum Receiver

As shown in Figure 9, the incoming signal is de-correlated by a matching PN spreading sequence. The receiving equipment must generate an equivalent PN Gold-Code sequence using the same PN generator as the space transmitter.

The generated code must be shifted in time to align with the transmitted code. Since this time delay is not known, the time-shift is an iterative process performed by the receiver. Effectively, the receiver attempts a de-correlation and measures the resulting waveform peak. It continues this process until it determines it has successfully found the correct time-shift that matches the space link delay.

Upon de-correlation, the resulting BPSK waveform is processed by a standard BPSK receiver. After the bit stream is recovered by the symbol-synchronizer, it is passed to a frame-synchronizer. This component locates the start of each RILDOS message and resolves any phase ambiguity, thus ensuring no data inversion. Acquisition time for the RILDOS signal would be expected to be on the order of less than 2 seconds. Since a frame only repeats itself every 10 seconds, the worst case acquisition time would be if the signal was acquired just after the beginning of the first message frame header. This would increase the acquisition frame to just greater than one full message frame.

As described previously, the processing of the telemetry signal is accomplished by its own dedicated receiver. This receiver does not know of the presence of the

RILDOS signal and processes the telemetry signal as it would as if it was not there.

IMPLEMENTATION

Rather than dictate a single product or mandate a hardware design for the RILDOS standard to use, the approach has been to define the standard itself in great detail and make it an open standard. This enables the community to take it and implement their own hardware and software for the space and ground ends of the link. So long as the standard is adhered to, it should be interoperable between the different receivers. The following section on implementation thus only provides an overview at the top level of how the space and ground products could work.

Space Transmitter

For the space end of the RILDOS signal, only a simple transmitter is required, and the transmitter can operate in an open loop mode, with no receiver feedback required. There are two possible paths for incorporating the RILDOS signal transmitter into the satellite's downlink.

The first path would be where a separate RILDOS modem is used to generate the signal and the resultant RF signal is then summed with the primary downlink signal. This approach provides maximum reuse of existing modems and designs, in that no alteration is required to the components in the primary transmission path. The RILDOS modem is also fairly straightforward and low risk to implement. Additionally, should there be an issue with the RILDOS modem or signal generation on orbit; it will not prevent the primary telemetry signal from being generated or broadcast.

The second path provides a smaller power, mass, and volume approach for small satellite developers. By incorporating the RILDOS signal generation path into the primary modem, only a single radio and RF path is required upon the satellite. With the market now providing options for software defined radios, it is possible for spacecraft radio vendors and developers to combine the functions required for the RILDOS signal into the very same software defined radio used for the primary mission downlink.

Either path may prove tempting to satellite developers. The decision of how to implement the RILDOS transmission on any given satellite will be highly dependent upon the mission parameters and design constraints. Hopefully, future off the shelf modems destined for use on small satellites will have the RILDOS capability built in and ready for mission operations upon just a few configuration parameters being set.

Ground Receiver

The combined telemetry and RILDOS downlink is processed by two separate receivers. The telemetry receiver is used to process the expected telemetry waveform. For example, if the telemetry signal is a 100kbps, BPSK waveform, the telemetry receiver would be a standard PSK receiver. The second receiver is used to process the RILDOS spread-spectrum signal. The diagram below (Figure 10) illustrates the ground receiver processing.

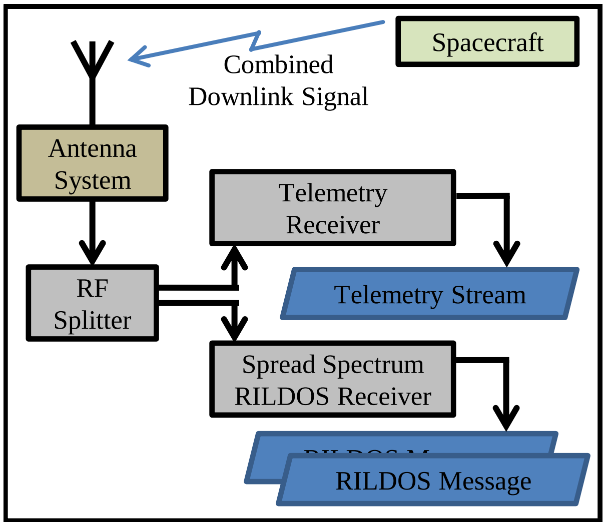


Figure 10: RILDOS Data Path Through Receivers

As shown in the Figure 10, both receivers are presented with the same waveform. The telemetry receiver processes the telemetry downlink signal as if the RILDOS signal was not present (since it is spread, it simply appears as a low-grade noise contribution). The spread-spectrum receiver processes the RILDOS signal by de-spreading the incoming waveform. As shown in Figure 7 above, after de-spreading, the RILDOS signal appears and can then be processed.

In practice, the two receivers may be combined in a single modem, so that a small satellite operator only has a single device to provision that then provides the telemetry and the RILDOS messages. The modem design may allow for separate TCP/IP ports for the telemetry and RILDOS messages, allowing additional or multicast distribution of the RILDOS messages while preserving the privacy of the telemetry data stream.

OPERATIONAL CONCEPTS

Examining the operational concepts for a RILDOS system is also important, as these potential scenarios provide a starting point for discussions among the many parties that are deeply vested in small satellite operations and space situational awareness. While the exact operational concepts that are implemented using RILDOS will vary and then evolve, three different communities can be identified and discussed initially. Those three groups – the owners and operators of satellites that have implemented the RILDOS standard, the "neighborhood" of nearby satellites, and the broader space situational awareness community – all can directly benefit.

Owner / Operator

The initial focus of the RILDOS standard is to solve the operational challenges that owners and operators face with their newly launched small satellites. This comes to the fore when examining several of the operational concepts that they can implement using RILDOS.

The first operational concept to examine is how the satellite operator could enable the RILDOS broadcast on their spacecraft to begin upon deployment. From the very first seconds of the spacecraft operating it would be clearly identified and its location would be available. The crucial first pass would be scripted differently. If the RILDOS signal has already been received by another party – either a neighborhood partner or a space surveillance program (see following sections) – they may have already had their exact identification and orbital elements provided to them and the first contact would not require any searching or analysis. If that were not the case, then the search would be for the RILDOS signal, which may only take a minute or two to survey the cluster. From the data in the now collected signal, the orbit would be quickly propagated and the full set of antenna pointing angles generated. That sequence of tasks may only take a few minutes and happen in the very first available pass opportunity, versus the current approaches in which it may take several hours or days to accomplish a first contact.

Another operational concept that the satellite owner can explore is how they would choose to use the area in the message format reserved for spacecraft use. As noted in the discussion of the message format, this area can be filled with any data that the operator chooses. That data area, which can be in a proprietary format and even subcommutated for more unique bit space, permits the return to ground of short high priority messages. Naturally, this message space pales in comparison to the much larger data stream from the nominal telemetry stream, but under certain conditions it may be very valuable. In the case where the RILDOS signal is broadcast continuously and there are RILDOS message collection and distribution services, the operator can get this message during times that the satellite is out of contact with their ground system, but when the RILDOS message is being collected by other stations that cooperatively monitor RILDOS broadcasts.

A variation on the use of the reserved area is that the data schema could be shared with users of the service the satellite provides. This would permit additional awareness of service status, planning requests, or capability to those users on a real time basis without sharing the entire telemetry stream with them or requiring them to obtain higher performance modems and RF chains. This would be especially useful for service users who are isolated and may have challenges connecting to the network.

Neighborhood

It is not only the satellite owner and operator who benefits from the use of the RILDOS standard. Other satellite operators who have satellites in orbital proximity or who are launched in the same cluster also can benefit from the widespread adoption of the RILDOS standard, even if their satellite does not implement the standard. As the RILDOS message is unencrypted, it is a free air broadcast and can be received by any party that has the proper equipment and knowledge to do so. Other satellite operators certainly have the knowledge and may very well have the RF processing chain equipment. Their motivation may arise from two situations.

First, in a launch environment, where larger and larger numbers of satellites are being deployed per launch, the cluster of satellites upon deployment may cause confusion as to the identity and location of their own satellite.[6] In this case, the only option for a satellite operator may be to attempt contacts with all the cataloged objects. These objects can be misidentified by the JSpOC or can be remapped by the JSpOC as further information is received. Additionally, while JSpOC will attempt to keep their catalog as fresh as possible with Two Line Element updates (TLEs), due to the architecture, capabilities, and other operational priorities of the Space Surveillance Network that may not be possible. Thus the TLEs may be out of date or inaccurate, leading to the confusion and challenges for all satellite operators in the cluster. Should a given satellite operator have a RILDOS capable receipt chain, they can then tune it to search for the RILDOS enabled satellites in the cluster, even if their own satellite is not RILDOS enabled. Once they do so, they collect short message bursts from each of them. This enables them to correlate the satellite in the cluster to the transmission, removing one more variable from the overall problem they have to solve.

The second case for neighborhood monitoring occurs when there are satellites that are operating in close proximity or who may have orbital close approaches. The typical operational concept in this case is to rely on the TLEs provided by JSpOC to perform regular Collision Avoidance (COLA) analysis. As with the launch and early orbit situation, the TLEs may be out of date, inaccurate, or misidentified, leading to an incomplete COLA analysis or one that may seem trustworthy, but in fact is misleading as to the true risk and danger involved in the conjunction under analysis. In these cases, if the "visitor" satellite is RILDOS enabled – even if the "home" satellite is not RILDOS enabled, planning to receive their RILDOS message on a regular basis provides accurate and timely orbital data. That data can be propagated and covariances calculated, enabling a higher confidence close approach analysis than what is possible with TLEs only.

Space Situational Awareness

Building upon the operational concepts highlighted for a neighborhood use of RILDOS, the community use of RILDOS can also improve global space situational awareness. If many satellite operators were to use the RILDOS standard, it would become a timely investment for many of the agencies tasked with providing space situational awareness to initiate programs that provide RILDOS monitoring. A program for this may have numerous RILDOS receivers set up across some logical geographic dispersion of sites. RILDOS signals of satellites overhead, and are added to their database of satellite identity, orbital data, and status. Ideally, that information would also be published for the entire community to share and be beneficiaries of. Realistically, it would not replace the other space surveillance systems (such as the SSN) that some countries may have, but rather augment them and provide unique information that helps characterize the status of each satellite.

There are some limitations to this approach. The first is that the system deployed would need a great many receivers – perhaps a few dozen to start with, but more as the system grows. The next is that the receipt of signals is somewhat happenstance if the RILDOS signal from a given satellite is only broadcast while the primary downlink is underway. This limits the temporal opportunities to only when the satellite is in contact with its ground station and also may impose downlink beam footprint constraints if the downlink beam uses a directional antenna or dish versus a bi-cone or omni-directional antenna.

One aspect that may mitigate these constraints would be if satellite owners and operators determine that the value provided by a broader RILDOS monitoring system is worth their support, they could have the RILDOS radio signal in a continuous broadcast mode. This would eliminate the temporal constraint for receipt only while in primary contacts, and as the footprint from the continuously broadcast signal would pass over monitoring stations at some point in the day, it would significantly reduce the footprint constraint. Even though the RILDOS signal is designed to be a very low power signal, potentially with only a single digit watt drain on the power bus of the satellite, each operator would need to make the determination if continuous broadcast mode is acceptable within their mission constraints for power, duty cycle, and satellite operations.

Even if a limited program for global RILDOS signal monitoring were implemented and constrained by the limited broadcast of RILDOS signals, there are still benefits to the small satellite community as a whole. If the message data were available on a searchable, real time basis, it could be used in near real time by the satellite operations community for identification and conjunction analysis, improving mission operations, reducing fuel use by eliminating unneeded orbital adjusts, and providing higher solution confidence in the truly risky conjunction scenarios. If continuous broadcast were adopted, those satellite operators could monitor the critical status of their satellite on a 24x7 basis through the program level monitoring of their emergency flags and user defined data areas in the RILDOS message. This would hopefully provide them enough warning to respond and prevent an anomaly from becoming a mission ending event.

STEPS FORWARD

The path from proposing a concept for a standard to formalizing a standard to operational implementation of a standard can be a long and arduous one. For RILDOS, the problem it attempts to solve grows as every next cluster of small satellites is launched.

Spurring discussion of the proposed standard is valuable within the small satellite community. There are several aspects of how the standard will be used by operations that bear further discussion, namely the assignment of spacecraft numbers and deconfliction of the spreading code for different missions on the same launch. The discussion that occurs may lead to simple approaches to coordinate the decisions of numerous operators – such as a simple website registry – or it could lead to involvement of key industry associations such as AIAA. Quick publication and implementation can help lead to improvements in the RILDOS standard gained through operational lessons learned.

The authors propose to generate an initial draft standard and post it upon key forums or websites for the small satellite community discussion. Additionally, we are investigating the design and prototyping for both a RILDOS enabled satellite transmitter using a software radio as well as incorporating a RILDOS receiver in a ground TT&C modem. As these steps are accomplished, the implementation lessons learned and operational knowledge gained will continue to be shared with the small satellite community.

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