# JANUS: the genesis, propagation and use of an underwater standard


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JANUS [1] is a robust signaling method for public underwater communications. It has been developed at the NATO Undersea Research Centre (NURC) with the collaboration of academia, industry and government. The performance of JANUS is evaluated between fixed and mobile nodes over distances up to 11 kilometers. The packet and bit error rates are computed as functions of signal to the noise ratios (SNR) and *time spreads* over periods extending from hours to months. Signal correlation times are computed for a time-variant acoustic channel. Long-term field experiments in 2008 and 2009 have helped quantify the robustness of JANUS during severe environmental conditions that adversely affect acoustic energy propagation. A cabled network of oceanographic instrumentation measured the ambient noise, water temperature, water velocity, internal wave and tidal information. These results provide a fundamental metric for estimating underwater network information throughput.



Keywords: JANUS, underwater communication, correlation time, time spread, acoustics, information throughput, underwater standard


## 1 Introduction

Interoperability of diverse systems is essential in a collaborative world. International agreements have established communication standards which allow interoperability for the 'terrestrial world'. In the underwater world of communications there are essentially no standards or regulations. There is no international body with effective jurisdiction. JANUS is a signaling method which complies with the *United Nations Convention on the Law of the Sea (Article 1)* [1, 2] and with the *NATO Undersea Research Centre Marine Mammal Risk Mitigation Rules and Procedures* [3]. The Law of the Sea provides one definition of pollution as "to directly or indirectly introduce energy into the marine environment" which is interpreted by commercial, military and geopolitical interests. JANUS is a compliant, publically available and robust communications method.

A central purpose of NATO is interoperability. A central requirement of communications is a standard. JANUS combines the public need for a standard and the NATO need for interoperability. These needs have lead NURC to establish an underwater standard for public use. The two primary purposes for JANUS are to announce the presence of a node and to establish the initial contact between dissimilar nodes. These purposes are similar to the 'Channel 16' radio usage at sea and on land. When possible, depending on channel characteristics, signal to noise ratios and hardware capabilities, JANUS may facilitate more bandwidth efficient methods of communication.

The ability to estimate information throughput (e.g. theoretical Shannon limit [4] at a given channel capacity) for a complex system (network) is predicated upon common methods and metrics. JANUS provides a common signal facilitating a common metric. To date, close to ***one hundred thousand*** JANUS packets have been sent. Underwater communications needs a global ocean model for the acoustic channel. Existing and future JANUS data will be made available for such a purpose.

## 2 JANUS signal and its creation

JANUS is a digital signaling method that uses *Frequency-Hopping Binary Frequency Shift Key* (FH-BFSK) modulation. This method has been chosen for its robustness and ease of implementation on existing

[1] In ancient times JANUS was the god of gates, doors, beginnings and endings.

underwater assets. The digital portion of the JANUS signal is proportional to its central frequency.

The central frequency of a transmission establishes the bandwidth. The bandwidth determines the allocation of frequencies for each bit. Each bit is ensonified for a proportional period of time with a precision of 25 parts per million (ppm). The mathematical tools necessary to create a JANUS signal, encode it in a desired frequency band and decode a received signal are publically available at several sites including at: http://nrcsp.zftp.com/users/janus-tmp/ [5, 6]. Below is a spectrogram of the simultaneous transmission of a JANUS message in four different bands. The length of a JANUS message is inversely proportional to the band in which it is transmitted.

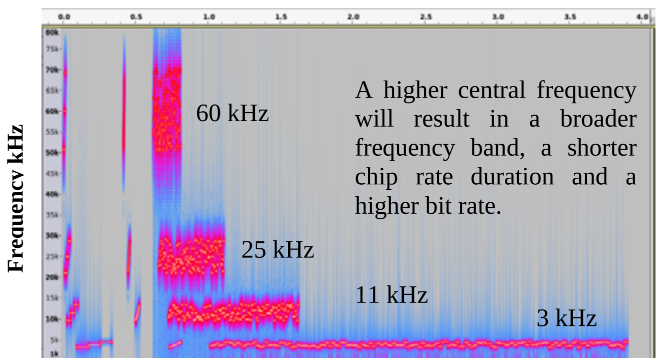


**Fig. 1**: A spectrogram (X-axis time= 4 seconds, Y-axis frequency= 2-70 kHz) of the same JANUS message in four different frequency bands. In the 9-14 kHz band, with 11520 Hz as the central frequency, there is 160 Hz of separation between 'bits' and the chip rate duration is 6.25 milliseconds.

### Encoding: user inputs

There are four required user inputs for encoding the first 64 bits of a JANUS signal that include: sample frequency, name of output file, output format (e.g. .wav) and the name of an external file. The external file (in XML format) contains additional information such as the transducer central frequency, JANUS version number, identification number of sender, ***parameter set***[2] and the signal repeat interval.

Convolutional (2 to 1) encoding [7] is applied to the 64 bits resulting in 144 bits to be transmitted. These 144 bits are interleaved and orthogonal tones are chosen for each bit. A preamble of three wake-up tones and a hyperbolic frequency modulated (HFM) sweep are added in band. These to aid in time synchronization and JANUS message recognition. A period of silence occurs between the wake-up and the HFM to allow *sleeping hardware* to come to life. Another period of silence occurs after the preamble to allow for dispersion of the preamble energy before the arrival of the first bit.

Optional user inputs include *urgency of message* and a *payload*. The payload may contain up to $2^{12}$ bytes of data (4096 bits), which are appended to the first 64 bits of information.

### Encoding activated processes

The encoding process utilizes the transducer's central frequency to *map* 13 pairs of orthogonal tones into the usable acoustic band of that specific transducer (as specified by the manufacturer). The central frequency also determines the *chip rate* – the time over which each bit is ensonified. A JANUS signal uses only 1/3 of the central frequency of a transducer as its bandwidth. As an example: a transducer with a central frequency of 9000 Hz will have 3000 Hz of bandwidth (i.e. 7500 to 10500 Hz).

### Decoding process

A matched filter is used to recognize the wakeup tones and the HFM sweep. The time of the matched filter detection provides good *time alignment* to begin the decoding of the first and subsequent bits. Each ensonification existing during each chip period is evaluated as being either "0" or "1" until the message ends. The resulting time series of "0s" or "1s" is de-interleaved and Viterbi decoding [7] is applied to the bit stream. The interpreted bits are written into a text file (e.g. *decode.txt*). Many additional diagnostic outputs are provided to the user including the number of errors in the packet (before and after Viterbi) and the duration of each chip. We have used an arbitrary SNR level of 5:1 as the *noise floor* discriminator. Please visit a JANUS website for the Matlab code which provides much more detail.

JANUS is relatively simple to use and several groups or researchers and manufacturers have been successful at implementation. The requirements are minimal. JANUS software has been installed on fixed and mobile nodes including AUVs with towed arrays. Most PCs (e.g. *PC104*) have adequate sound cards (outputs) and microphones (inputs) for encoding/decoding. JANUS is documented and can be introduced without lengthy training or instruction.

## 3 Experimentation at Sea

The most extensive use of JANUS to date has been during the SubNet experiment from May to September 2009. The system included 5000 meters of cable, multiple sources, multiple receivers, environmental sensors and an AUV with gateway buoy. The system was installed off the coast of the Island of Pianosa [8], south of Elba in the Mediterranean Sea. A satellite telemetry link allowed

[2] The ***parameter set*** identifies the hardware manufacturer, capabilities, types of modulations and bands available, RF and optical (similar to vehicle identification number – the VIN for automobiles).

experiments to be performed remotely with signals from collaborators from Italy, Germany, US and United Kingdom.

The three fixed bottom mounted modems (transmitting nodes) T1, T2 and T3 were on 1.5 meter high tripods at depths of ~60, ~80 and ~70 meters respectively. They were located at distances of 1500, 2300, and 700 meters from a moored vertical array (VA) of four hydrophones H1, H2, H3 and H4 at ~20, 40, 60, and 80 meters depth respectively. A thermistor string attached to the VA collected temperatures at 11 depths every 2 minutes.

Mobile transmissions, from an AUV and towed acoustic sources, were completed up to 11000 meters from the VA. The distances and durations of the experiments were designed to simulate real AUV deployment scenarios. Other experiments have been completed in Europe, North America and Asia. To date, the furthest transmission of JANUS was completed by FWG [9] in the Baltic Sea in 2010 at a distance of 22000 meters.


**Fig.2: SubNet 2009** - Island of Pianosa, hardware and cable locations in red, the high-resolution bathymetric survey in red-blue to the east. The CRV Leonardo and a REMUS AUV were used as mobile platforms (1-70 kHz).

# 4 Signal propagation and decoding

Propagating acoustic energy underwater travels along many paths. Sound speed variations, ambient noise fluctuations, sea surface roughness and bottom properties all contribute to the amplitude and composition of a received signal. The acoustic energy, representing each bit, may arrive at a receiver along many different paths. This phenomenon is referred to as *multipath* where each path may have a different arrival time. The time from the first arrival to the time of the last arrival (relative to an arbitrary sound pressure level) is referred to as *time spread*. Interfering multipath arrivals with phase changes will make a signal less coherent and generally result in more decoding errors. It is important to note that with strong internal waves the intensities and paths can change within just a few seconds. Hence signal coherence times can be very short [10] (Tielbürger 1997). In networking applications, coherence times influence the choice of *medium access control* (MAC) strategies [11] (Tomasi et al. 2010).

**Time spread (multipath) variations**

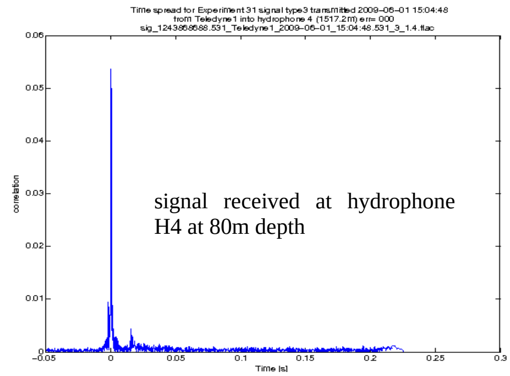


**Fig. 3: Weak multipath** is easier to decode**.** Normalized matched filter output (Y-axis) during a time window (X-axis) of 300 milliseconds. The T1 to H4 distance is 1500 meters.

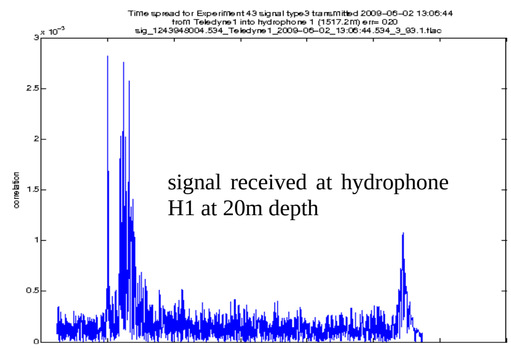


**Fig. 4: Strong multipath** is harder to decode**.** Normalized matched filter output (Y-axis) during a time window (X-axis) of 300 milliseconds. The T1 to H1 distance is 1500 meters.

**Time spread variations versus depth and distance**

The ocean is rarely homogeneous in the vertical and arrival times (time spreads) usually vary with depth. When the upper *mixed layer* has a different sound speed than the underlying water, both the intensity and the arrival times will vary in the vertical. This is apparent in Fig. 5 below showing the theoretical paths along which acoustic energy propagates using the Bellhop model [12].

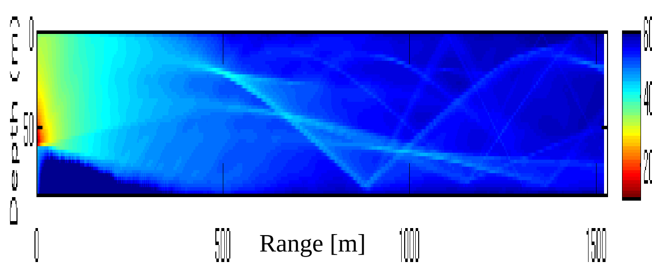


**Fig. 5: Bellhop** acoustic ray tracing from T1 to VA (a distance of 1500 meters) The Y-axis= depth. The colorbar represents transmission loss in dB. Many s*hadow zones* exist including at the depth of 15 meters where at distances of ~600 and ~1200 meters the acoustic energy intensity is greatly diminished.

### Time spread variations versus distance

In figure 6 below, the number and intensity of multipath arrivals changes with the distance between the transmitter and the receiver. There are two strong multipath arrivals (in red-yellow) at short distances (500 meters) associated with surface and bottom reflections.

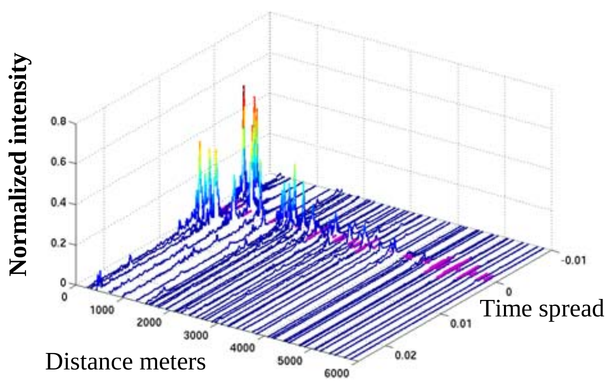


**Fig. 6: Normalized multipaths vs. time spread** arrival intensities from a towed source over a distance from 400 to 6000 meters. The *time spread* window is 300 milliseconds.

### Raw chip error rates (CER) and SNR

The CER is a measure of the decoding success of each ensonification period (i.e. *chip*). Because of its convolutional encoding [7] JANUS requires two chips for each bit of information. The bit error rate (BER) is a measure of end- to-end information error. Figure 7 below shows the raw BER for ***32134*** JANUS transmissions (over several months). The shorter the time spread the better the decoding. The red the colours indicate the more successful decodings. The light coloured decoding contour lines have been added. A *chip rate artefact* hump is seen at 6.25 milliseconds.

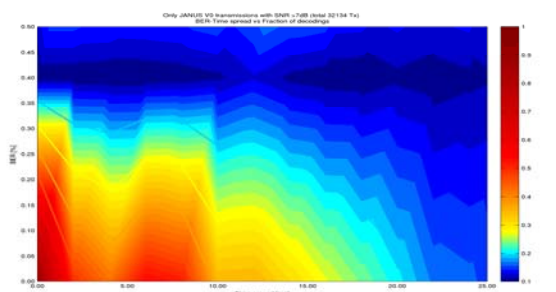

**Fig. 7 BER** for ***32134*** JANUS transmissions from any source, fixed or mobile, at any time with a SNR at or above 7dB in the 9-14 kHz band. The X-axis is the first 25 ms of time spread and the Y-axis is the BER from 0-0.5%.

There is a strong relationship between time spread and CER [13]. Figure 8a below shows the percent of chips ***without*** errors for 512 packet transmissions with an SNR from 2 to 4 dB. Figure 8b shows a very similar percent of chips ***without*** errors for 2361 packets with SNR from 9 to 11 dB. The *peaks* (in red) represent a low CER and low time spread. For signal to noise ratios above 2 dB, time spread is the dominating factor for evaluating CERs.

With knowledge of the channel characteristics as functions of depth and distance, AUVs may adapt their behaviour to optimise communication and detection activities [14]. The behaviour of an AUV may include to 'not communicate' when the environmental conditions do not provide adequate *channel capacity* for the desired information throughput. The power levels can be adapted to the *near-far* requirements of a network and the current channel characteristics.

An *Ephemeris Packet Error Rate* (EPER) may be viewed as the cumulative effects of the current channel capacity, probability of future channel capacity, AUV behaviour and the mobility of other assets, including the probability of a current or future physical location(s).

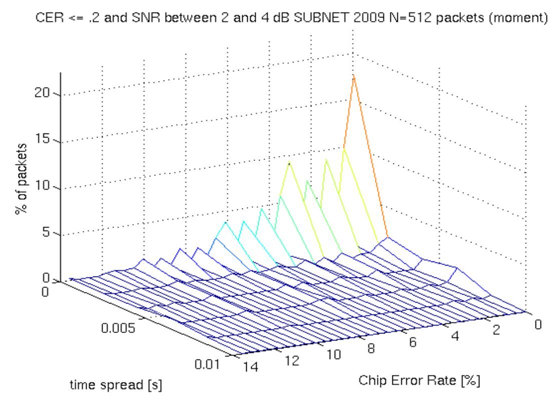


**Fig. 8a CER** vs. time spread and decoding success at 2 to 4 dB of signal (512 packets). The red peak is at low CER and time spread and represents good decoding results.

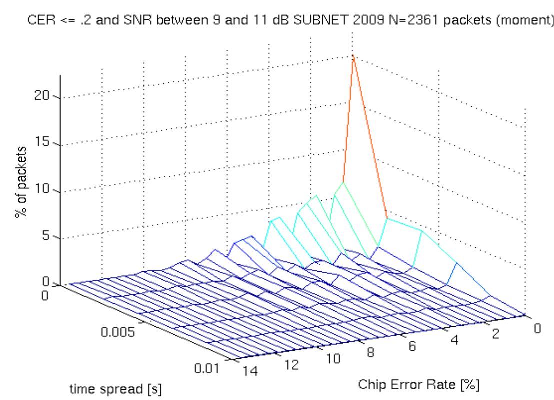


**Fig. 8b CER** vs. time spread and decoding success at 9 to 11 dB of signal (2361 packets). The red peak is at low CER and time spread and represents good decoding results.

### Averaged Packet Error Rates (PER)

The ability to transmit information depends not only on the bit error rate but also the PER. Unsuccessful packets need to be resent. Figures 9a and 9b below are 10 minute averages (20 packets) for 4359 packets and 1704 packets. Data are for transmissions from T2 to H4, a distance of 2300 meters.

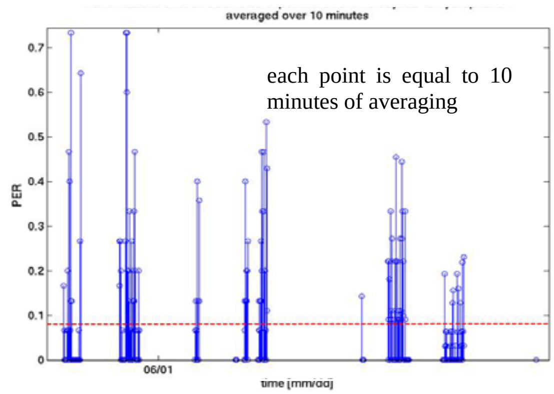


**Fig. 9a: PER overview** of 4359 packets sent during 9 days, 30 May 02:00 to 07 June 17:00 2009. The average PER is 8.6% (dashed red line).

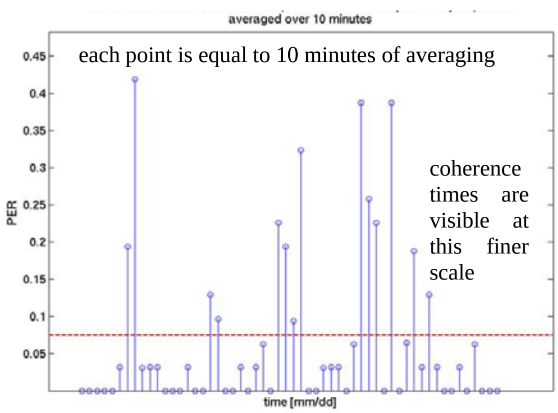


**Fig. 9b: PER detail** for 1704 averaged packets sent during ~10 hours, 30 August 22:00. The average PER for 10 hours is 7.2% (dashed red line); one packet sent every 30 seconds.

**Environmental factors: temperature, currents, wind and shipping**

The ocean is spatially and temporally under sampled and generally requires a statistical approach to influences of temperature, wind and water velocity fluctuations [15]. In May 2009 the seasonal thermocline had not yet been established. There were large and rapid (*internal wave driven*) temperature fluctuations (4°C in a few hours) as shown in figure 10 below. As the season progressed, a well-mixed isothermal layer developed and extended from the surface down to ~20 meters.

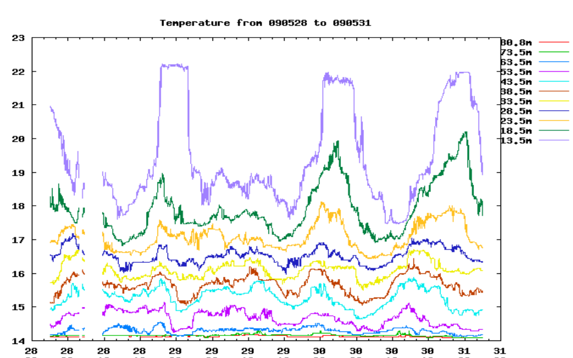


**Fig. 10**: **Thermistor string** data for 3 days from 11 temperature sensors extending from 13 to 80 meters of depth.

The ocean currents (<0.25 m/sec) measured with an ADCP on the east side of Pianosa are primarily driven by the small tidal fluctuation (0.3 meters) and the winds associated with barometric changes of the atmosphere. The winds were light, typically less than 4 m/sec, with occasional short periods over 10 m/sec. The stronger winds and shipping noise contributed to high ambient noise levels during which JANUS continued to perform well in the 9-14 kHz band. Pianosa, although off limits to all vessels within 1 nautical mile, is subject to substantial low frequency underwater acoustic noise due to fast ferries and slower moving bulk-container ships.

# 5 Conclusions

JANUS has been successfully decoded without errors under difficult conditions including: signal levels as low as -3dB into the noise. Low frequency (3 kHz) transmissions have been made up to distances of 22 km and high frequency transmissions (70 kHz) over short distances less than 500 meters. The changing oceanographic conditions, strong multipath environments, shipping, wind noise and Doppler shifts (3.5 m/sec relative speeds) have tempered JANUS. The results of the multi-national experiments using JANUS have been promising enough to qualify for submission as a NATO Standardization Agreement (STANAG) for underwater communications and networking. Other standards beckon to be created for underwater spectrum allocation for a multitude of uses.

JANUS can be used for many applications. The position, speed and heading of surface ships (*e.g. AIS*), offshore windmills and geophysical exploration platforms can be announced acoustically. Such transmissions will aid underwater navigation, underwater time keeping and submarines in avoiding collisions at sea. There is still much refinement to be done to JANUS including: automatic Doppler compensation, adaptive equalization and the transmission of JANUS in more oceanographically diverse areas of the world. There have been efforts to standardize underwater communications before and there will be efforts after; JANUS is a step along the path that we must travel.

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"Da steh' Ich nun Ich arme Tor und bin so klug als wie zufor" – Goethe.

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