The Galileo Spacecraft: A Communications Legacy for Future Space Flight

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Abstract

The Galileo mission to Jupiter has implemented a wide range of telecommunication improvements in response to the loss of it's high gain antenna. Among the communications enhancements that have been made are the use of advanced compression techniques, packetized telemetry, new error correcting codes and algorithms, more efficient modulation, variable transmission data rates, routine ground antenna arraying (even between continents,) extremely sensitive ground receivers, and non-real-time automated data reconstruction. These together have resulted in a 20 dB (100 fold) increase in information being returned from the spacecraft at Jupiter, allowing the mission to meet the vast majority of it's science objectives using small, hemispherical antennas and an S-Band system. In fact, Galileo is currently the most advanced deep space craft in the world in terms of communications technology. While necessity dictated the use of these new techniques for Galileo, now that they have been proven in flight, they are available for use on future deep space missions. This telecommunications legacy of Galileo will aid in our ability to conduct a meaningful exploration of the solar system, and beyond, at a reasonable cost.

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1. INTRODUCTION

The Galileo spacecraft is currently in its prime mission, orbiting Jupiter and gathering information about the planet, its moons, and its environment. The fact that it can do this job without the use of its High Gain Antenna (HGA) is no small feat. When the HGA failed to deploy, after Galileo's first Earth flyby, the communications system was placed at a four order of magnitude (factor of 10,000) disadvantage. Without any changes, the communications link between the spacecraft and the Earth would have been capable of only about 10 bits per second. This is about one third speed of a competent typist! When one considers the amount of once-in-a-life-time science data that needs to be collected by such a mission, this rate is totally inadequate.

A number of changes were made to both the Galileo spacecraft and the Deep Space Network (DSN,) the Earth-based antennas and processing that NASA uses to communicate with all of its deep space missions. These changes resulted in a two order of magnitude (factor of 100) improvement [1]. When taken together with careful mission planning, Galileo is expected to achieve better than 75% of its science objectives.

NASA, and the world deep space community, will be facing a challenge of the same severity over the next 15-20 years. Figure 1 shows a history of deep space launches beginning with the very first mission (in 1968) and projecting launches into the future. An earlier version of this chart showed four or five launches each year beginning in 1999. This projection came from several planning exercises being conducted by NASA's Office of Space Exploration. When that chart was shown in a presentation to Daniel Goldin, NASA's Administrator, he remarked that it was not aggressive enough. His vision is to have 12 launches each year. Indeed, this is consistent with Mr. Goldin's move toward having many more, but much smaller, missions. His philosophy is known as "faster-better-cheaper."

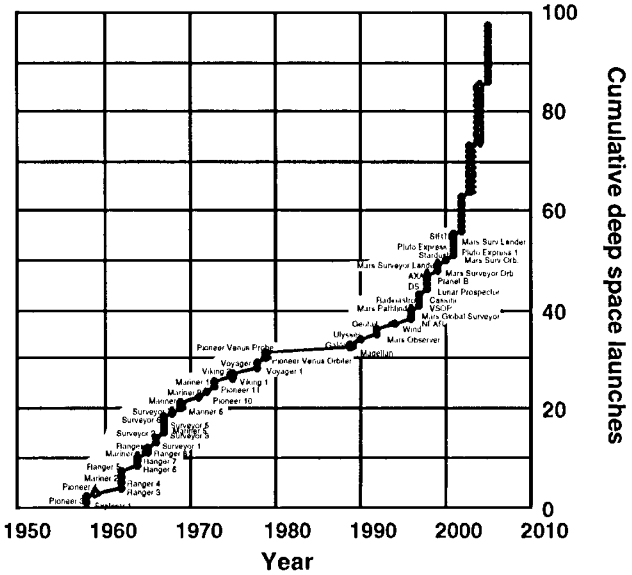

Figure 1
History and Projection of Deep Space Launches

In addition to the increased number of launches, these missionstend to last longer. The Mars program will concentrate on returning soil and rock samples - requiring missions of at least three years duration. An Outer PlaneT program will focus on studying Pluto, the Kuiper belt, and other small bodies far from Earth. Such missions will typically be of ten year duration or longer. An Origins program will focus on the search for planets around other stars, placing sets of spacecraft in formation to observe for many years.

The instruments that will be flown on future missions are likely to require increased communications capability. The trend is toward two and three dimensional instruments such as imaging spectrometers.

With the number, duration, and data requirements of missions all increasing, it is easy to be convinced that the communications capability between deep space and Earth will have to increase by at least a factor of 100 by the year 2015. This is equivalent to increasing the number of DSN antennas (and the associated signal processing and data distribution) by a factor of 100. Based on the current technology for building large antennas, this would cost about $30B in current American currency.

Although $30B may seam low (the current capital investment in the DSN is about $2B which might lead one to conclude it would cost $200B) it is unrealistic to assume that this level of support will be forthcoming for the DSN. The current NASA budget is only about $14B per year and most goes into the piloted (Space Station and Shuttle) programs. Also, any money spent building antennas could have been spent building those dozen spacecraft each year!

Luckily, there are other ways to increase the effective capacity of the deep space to Earth communication link by factors like 100 - Galileo has demonstrated this. When the Galileo spacecraft was built, it had a state-of-the-art communications system. By the time the HGA failed to deploy, communication technology had advanced to the point that it was possible to increase the efficiency by 100. The techniques that were used are shown in Figure 2. All of these improvements, with the exception of one, are applicable for future deep space missions. The top slice of the chart, labeled "ultracone" is not. The ultracone [2] is an optimized detector for the 2.4 GHz radio frequency which Galileo transmits to Earth. No future missions are planning to use such a low frequency.

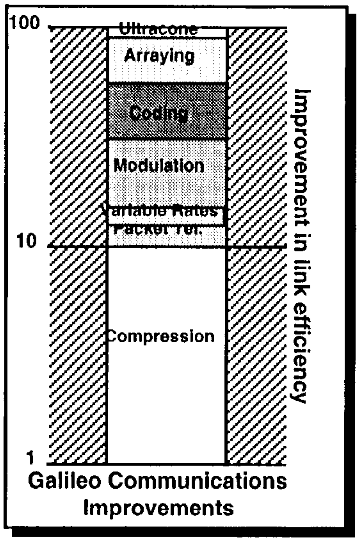

Figure 2
Improvements in Galileo's Communication System

The Galileo spacecraft has served the role of communications technology pathfinder for future missions. Because these technologies have been proven in Galileo operations, they are now available to other missions. Also, since NASA has paid for upgrades of DSN equipment, the technologies are available at a reduced cost.

The remaining sections of this paper explain each of the communications system improvements and discuss how they are applicable to other missions. Using the example set by Galileo, NASA and the world space community will be able to meet their deep space communications challenge.

2. DATA COMPRESSION

By far, the biggest gain in communications efficiency for Galileo comes from the data compression. Data compression refers to a set of methods for reducing the amount of transmitted data needed to represent the actual information captured by a sensor. For example, consider the phrase "Data compression for Galileo." One might compress this phrase to "cmpresion 4 GLL." Most people who speak English will have no trouble expanding the word "compression" to "compression" and "4" to "for." Communications experts will automatically add the word "data" before "compression." Galileo spacecraft project personnel will recognize "GLL" as the official abbreviation for "Galileo." Hence, English-speaking communications people on the Galileo project will correctly expend the phrase. The original phrase is 29 characters long while the compressed phrase requires only 16 to represent the same *information*. The difference between the information content of something and the number of characters required to represent it can result in substantial compression.

In the above English example, a *compression ratio* of 29:16 was achieved - almost 2:1. In fact, most English text can be compressed by about 2:1 without loss of information. Anyone who has downloaded text files over the internet has used such algorithms, as has anyone using a disk-doubling utility on their personal computer. Such compression is called *lossless* because all the original information can be gleaned from the compressed data.

Another, more powerful kind of compression is called *lossy*. This is unfortunate because it leads one to reject such algorithms a prioi. This reluctance was common in deep space missions - until Galileo needed these algorithms. Now, all future deep space missions are planning to use lossy data compression. Such algorithms can produce quite useful images, for example, at compression ratios as high as 40:1 as shown in Figure 3.

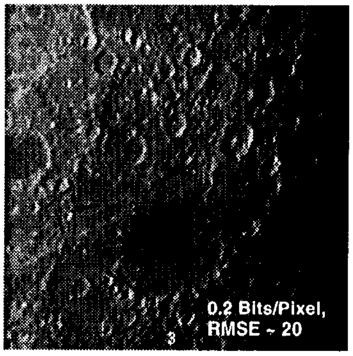

Figure 3
Planetary image after compression of 40:1

The data compression algorithm that gives Galileo most its efficiency gain is the Integer Cosine Transform (ICT [3].) The ICT is used to compress data from Galileo's imaging camera and spectrometer - the instruments that produce the most raw data. The ICT is one of a class of compression algorithms that analyzes an image, isolates its interesting features by measuring how randomly the pixels appear in small areas, and then transmits those areas with higher fidelity than the remainder of the image. Another algorithm in this class is the Joint Photographic Experts' Group (JPEG) algorithm, which is a standard for image transmission over the internet. Such algorithms can take an 800 x 800 pixel image, with 8 bits of data in each pixel, and compress it by about 10:1 so that the reconstructed image has an average error of only one level (1/256 of the total dynamic range) per pixel. The algorithm represented by Figure 3 is actually more advanced than the ICT or JPEG. It is known as *Subband Coding* [4]. The 40:1 compression achieved in the figure is at the expense of an average pixel error of 20 levels (20/256 of the dynamic range.) Although such images have reduced science value for some applications, they are more than adequate for preliminary examination of a region to target further, intense study.

3. PACKET TELEMETRY

The way spacecraft data is organized for transmission to Earth can have a large effect on the efficiency of the communications. Until Galileo, deep space craft used a scheme called *time division multiplexing* (TDM) to assemble data from various science instruments into a stream of bits for transmission. This scheme is shown in Figure 4. The stream is built up in a repetitive pattern with each instrument's data always placed in the same part of the pattern. In TDM, the position in time of a received bit indicates its source on the spacecraft. The problem with TDM is that, during various times in a mission, the amounts of data generated by the various instruments can change dramatically. There is little need for camera images, for example, during the cruise time between planets. For this reason, missions typically had many different TDM patterns stored in their computers. An appropriate pattern for each mission phase is selected in advance from the ground.

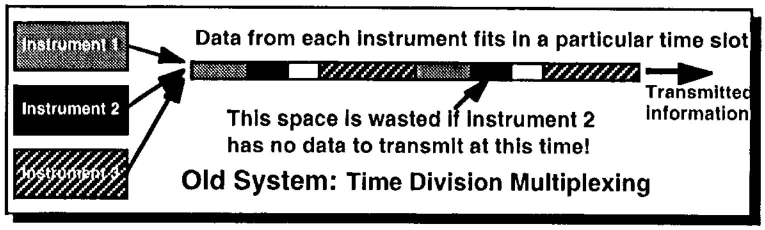

Figure 4
Time Division Multiplexing (TDM)

The existence of multiple TDM patterns presents two problems. First, one can never have enough patterns to satisfy all possible science scenarios - particularly if the patterns must be selected well in advance of their use. This means there will always be wasted space in the pattern. Waste occurs when it is an instrument's turn to supply data but none is available. A sequence of all zeros is typically sent in this case. The second problem is that each TDM pattern represents a set of spacecraft modes that must be tested in order to insure the reliability of the mission. The more TDM patterns, the more testing required.

An alternative scheme, now being used by Galileo, is *packet telemetry* and is shown in Figure 5. In a packet telemetry system, data is assembled from the instruments into a series of messages, called *packets*. Each packet contains data from a single instrument (actually, this is a simplification - but it will do for the purpose of this paper.) The packets are assembled into a data stream for transmission to Earth. There is no regular pattern, as in TDM. Instead, the number of messages is a function of data availability from the instruments.

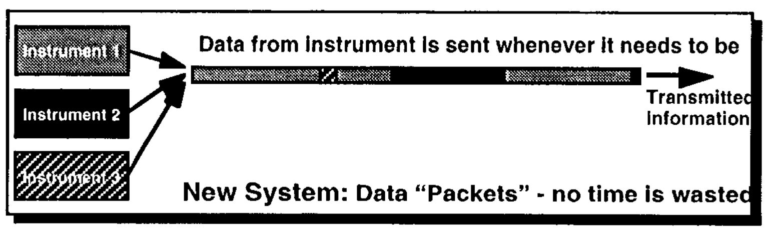

Figure 5
Packet Telemetry

Upon reception at Earth there needs to be a way to tell where the packets begin and end and which instrument's data they contain. This is provided in a *packet header*, a small amount of information attached to the beginning of each packet. The packet header typically contains the source instrument's identification, the time at which the data was acquired by the instrument, and the length of the packet. Since headers are not required in a TDM system, they represent additional data to be transmitted for a decrease in communications link efficiency. However, there is no waste with packet telemetry, so it ends up being much more efficient than TDM. Also, the message paradigm results in a standard interface between instruments and the spacecraft's central computer which can lead to reduced development and testing costs for spacecraft.

Packet Telemetry is not a new concept developed for Galileo. It is in common use for terrestrial communications, Earth-orbiting satellites, and communications within computer systems. In fact, there has been an international standard for packet telemetry in space systems for more than a dozen years [5]. All future deep space missions have already chosen this system over TDM.

4. VARIABLE DATA RATES

The Deep Space Network's antennas are all on the Earth. Deep space craft appear to the DSN like a stars in the sky - they stay fixed in the zodiac, at least for the short periods of time during a communications session. Each antenna has line of sight contact with a deep space craft for between about six and ten hours, depending on the latitude of the antenna and the location of the spacecraft. During this time, called a *pass*, the spacecraft's received signal changes intensity depending on how much of the Earth's atmosphere it traverses. The signal is weakest when the spacecraft appears at the Earth horizon, it gets stronger until it is overhead, and then weakens again as the spacecraft goes out of sight on the opposite horizon. The received signal strength follows a the smooth curve as shown in Figure 6. The amount of data (e.g. the number of bits) that can be received is a function of the received signal strength. The stronger the signal, the more bits per second, or *data rate*, is possible.

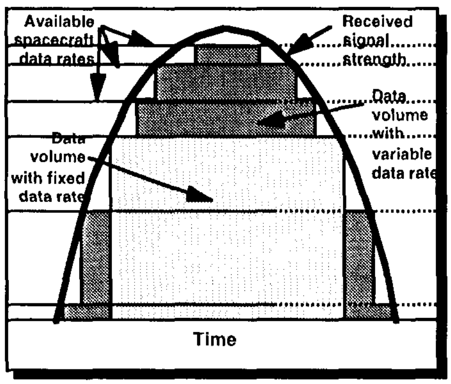

Figure 6
Use of variable data rates to maximize data return from deep space

All deep space craft built to this time (including Galileo) are capable of transmitting data only at a discrete set of data rates. In Figure 6, these possible data rates are represented by horizontal lines. Spacecraft prior to Galileo typically transmitted at only a single data rate for any pass. The signal strength was predicted in advance and an optimal data rate was chosen to maximize the bits received during each pass. In Figure 6, the large rectangle under the curve is the result. The area of the rectangle is equal to the number of bits received during that pass [6].

Among the changes made to the Galileo spacecraft and the DSN was the ability to change the data rate many times during a pass. The result is the area under the staircase-shaped function. The additional area over that of the rectangle represents additional bits returned during the pass. In order to facilitate this, new receivers were required for the DSN that could track the spacecraft through these data rate changes without losing data during the transitions.

Variable data rates can now be used by other deep space missions, although there is still reluctance to do so. This is because it requires a great deal of work to predict which data rates should be used when. This work is currently done in advance on Earth and the answers are transmitted to the spacecraft. In the future, an automated system in which the spacecraft and ground enter into two-way communications and adjust the data rate continuously is preferred. This is similar to the way internet communications is accomplished today.

5. MODULATION

All deep space missions that have been supported by the DSN have used a form of modulation known as Binary Phase Shift Keying (BPSK [7].) It the bit stream to be transmitted is represent by the function $d(t)$, which takes on only the values ± 1 as a function of time, then the transmitted signal has the form

$$A\sin((\omega t + \theta d(t)) = A\cos(\theta d(t))\sin(\omega t) - A\sin(\theta d(t))\cos(\omega t)$$
$$= A\cos(\theta)\sin(\omega t) - A\sin(\theta)d(t)\cos(\omega t)$$
$$= B\sin(\omega t) + Cd(t)\cos(\omega t). \qquad (1)$$

The constant A represents the energy of the transmission. The second line of the equality uses the fact that $d(t)$ can have only the value ±1. The constants B and C in the last line depend only on the *modulation index*, θ.

Until Galileo, the DSN receivers actually tracked the first, pure sine wave term in (1) and used the result to demodulate the second, modulated term. In order to maximize the energy devoted to each bit of data in the transmission, θ was chosen to be 90° for all transmission. This results in a signal of the form

$$A\sin((\omega t + (\pi/2)d(t)) = Ad(t)\cos(\omega t),$$

known as *suppressed carrier* [8] modulation because the pure sine wave term has been completely suppressed. Suppressed carrier modulation is not new for Galileo. It has been the preferred modulation type for communications with Earth-orbiting satellites. In order to use it for deep space, however, new receivers were required that could track at very low signal levels [9]. Now that these receivers exist, this more efficient modulation is available to all future missions.

6. ERROR-CORRECTING CODES

The performance of a communication system gets worse as the signal power decreases. One can use certain techniques to allow good reception at very low signal levels. One of these is error-correcting coding.

Consider the phrase "eror corekting kodes." People who speak English will most likely be able to correct the spelling to "error correcting codes." This is because English itself is an example of an error-correcting code. There is enough redundancy in the English language for us to correct most spelling errors without trouble. Anyone with young children has experienced this when reading a child's early essay work from school. Despite the fact the child has probably spelled half the words phonetically, the adult has no trouble reading and understanding the story.

Error-correcting codes for deep space use this same phenomenon for digital data. Figure 7 shows the performance of several codes. The horizontal axis is the energy devoted to each bit of data, normalized by the amount of noise in the system and expressed in decibels (dB.) The vertical axis shows the resulting bit error rate. The curve to the extreme right shows the performance of system using no error-correcting codes. The next curve shows the performance for one of the current NASA standard codes, the (7, 1/2) convolutional code. It is not important to this paper to discus how the individual codes work. It suffices to state that the substantial performance gain (more than 5 dB, or a better than a factor of three) results from adding a six bit shift register and some simple logic to the spacecraft.

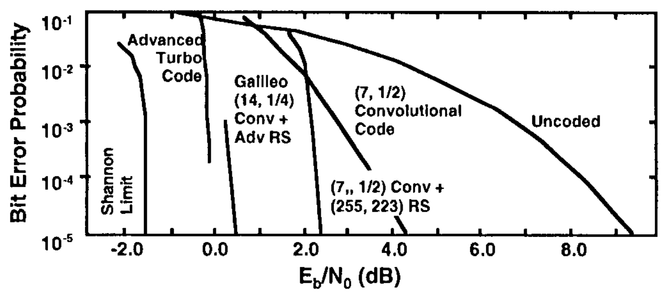

Figure 7
Performance of some error-correcting codes

The next curve shows the performance of the concatenated coding system that was used on Galileo before it was reprogrammed for orbital operations. The new Galileo coding system is shown next [10].

Some very advanced techniques were used to achieve this performance gain for Galileo. The amount of redundancy in the code is carefully controlled and varies with time. In addition, special decoding algorithms were implemented that can spend additional time on the parts of the received data stream with more errors.

Figure 7 also shows a new, more advanced code developed after the Galileo orbital mission design. It is from a class of codes known as *turbo codes* [11]. These codes, while quite different from the Galileo code, use many of the same decodng techniques. The use of very advanced error-correcting codes is part of the Galileoc's communications legacy.

7. ANTENNA ARRAYING

One can always increase the communications performance by making the receive antenna larger. The performance of the system is proportional to the antenna's area, or aperture. Since it was impractical (in cost and schedule) to build larger antennas for Galileo, existing large antennas were *arrayed.*

In antenna arraying, two or more antennas are used simultaneously to receive spacecraft's signal. The output from the antennas is processed to remove the effects of the antenna spacing and relative accelerations with respect to the spacecraft. The effects of the noise in the various antennas is also accounted for in the processing.

The arraying configuration for Galileo is shown in Figure 8. Since Galileo remains in the southern sky during its orbital mission, the DSN's Australia station has the best and longest view of the spacecraft. Hence the DSN's Canberra site is the center for the Galileo antenna array. In addition to the DSN's 70m antenna and two 34m antennas, the Australian Commonwealth Scientific and Industrial Research Organisation's (CSIRO) 64m antenna is arrayed. Also, during the period of time when Galileo can be seen from both Australia and California, the DSN's 70m antenna at it's Goldstone site is added to the array. The combined aperture from these antennas results in about three times the performance that would have been possible with only a single 70m antenna. Of course, this array can only be used for only that part of the Earth's rotation when all the antennas have a view of the spacecraft.

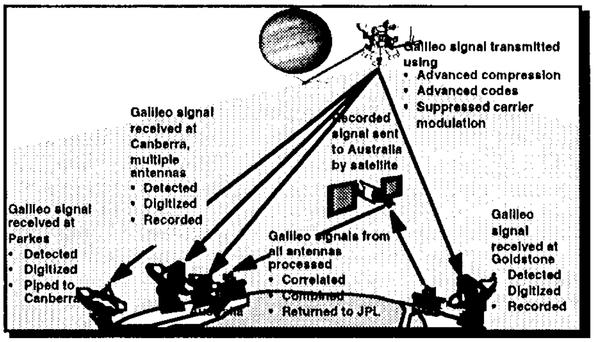

Figure 8
Antenna arraying for Galileo

Antenna arraying has been performed at the DSN before, for the Voyager 2 encounters with Neptune and Uranus [12]. Voyager's arraying was less sophisticated than that used for Galileo. For Voyager, each antenna received the spacecraft's signal and demodulated it to form a digital data stream. The digital streams were then correlated and summed to produce the arrayed signal. For Galileo, the carrier signals themselves are correlated and summed. The resulting summed carrier signal is then demodulated to form a digital data stream. The Galileo scheme, known as *full spectrum combining* [13], works at lower received signal levels and reconstructs the digital stream with greater integrity.

Another difference is that Galileo's arraying is performed on a routinely. The DSN equipment has been designed for easy configuration of arrays and the DSN staff has been trained to operate the arrays as part of their normal workload. Voyager's arrays were operated only a few times at critical points in the spacecraft's trajectory.

The new arraying algorithms that have been put in place for Galileo are available for future missions - but will probably used only for critical mission events. With the number of missions increasing, it is unlikely that future missions will be designed to require routine antenna arraying on the scale of Galileo.

8. ASYNCHRONOUS PROCESSING

The DSN is based on an architecture that dates from its inception in the 1960's. This serial architecture is shown in Figure 9. Radio signals are gathered by the antenna and passed to a receiver. The resulting data stream is passed first to one decoder, and then to another. Finally, decoded data is passed to an expander that undoes the compression present in the data stream.

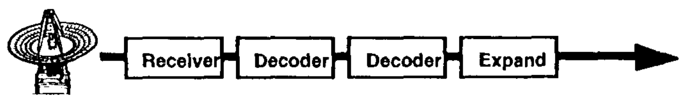

Figure 9
Serial processing in the DSN

Figure 9 is highly simplified. There are actually at least eight processors in the serial flow of data. Each processor lies in the data flow path. This means that if any one of them fails, the DSN will fail to process the data until a similar processor can be switched into the serial stream as a replacement or a completely separate serial chain is enabled. It also means that if a new processor is added to the DSN the entire DSN must be retested.

The new processors built to handle Galileo's communication in the DSN are configured as shown in Figure 10. The antenna still passes a signal to a receiver. However, as soon as digital data exists, at the output of the receiver, it is placed into a buffer. In the buffer, the receiver digital streams are managed as computer files.

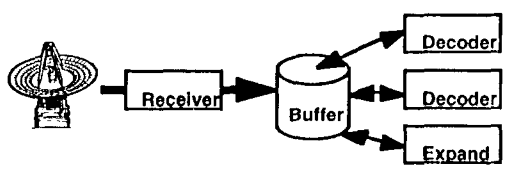

Figure 10
Asynchronous processing used by the DSN for the Galileo spacecraft

Each subsequent processor accesses the files it requires to do its job and places the resuts back into the buffer as new files. This architecture for the DSN is asynchronous - that is the processing of the stream occurs independently of the events that take place in real time in the receiver. Asynchronous processing was required by the Galileo communications system in order to accommodate the antenna arraying and advanced error-correcting codes.

There are several advantages of the asynchronous scheme over the serial one. First, each processor only has to interface with the buffer. This makes all the processors communicate in the same way. By using a computer file for the interface, commercial software can be utilized, lowering the development cost of each processor. No processor is in the critical path for the signal. Instead, one could have many decoders attached to the buffer that handle any files they happen to find there. If one fails, a second will be ready to take over. In the event that all the decoders fail, the computer files are still in the buffer, waiting for a repaired decoder.

New processors can be easily added to this architecture, without requiring the entire system to be tested.

Although the asynchronous processing used in the DSN's system for Galileo does not result in a communications link efficiency improvement, it does result in lower development and maintenance costs. The DSN is beginning the process of upgrading all its systems to this architecture. This is a low-cost legacy from Galileo for future missions.

9. CONCLUSION

It has been shown that most of the communications improvements that were made for the Galileo mission are applicable to future deep space missions. The technology will continue to improve with time, making the required factor of 100 efficiency improvement discussed in the Introduction easier in the future. The basic techniques, however, have now been proven in a real operating deep space mission - Galileo.

Figure 11 shows the results of forecasting such communication technology forward to the year 2020 [14]. All the improvements described in this paper are considered as well as two that were impractical for Galileo: higher frequency carrier signals (including optical communications) and larger spacecraft antennas.

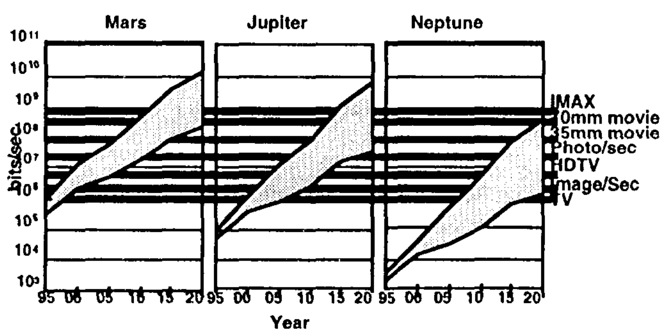

Figure 11
Forecast of communications technology

Three scenarios were considered in the predictions, which were made as pat of NASA's planning for the exploration of the solar System. These were communications relay orbiters at Mars, Jupiter, and Neptune. Future intense exploration of the planets will likely involve many simultaneous spacecraft. Relay orbiters can lower the cost of providing intense communications with the multiple spacecraft. Each spacecraft would only require a high rate link to the nearby relay.

The vertical axis in Figure 11 is the data rate that could be supported at that time. The curves bounding the dark areas represent conservative and aggressive estimates of communications technology. The horizontal lines drawn through the curves show the data rates required for some common data types, with aggressive compression applied. These range from broadcast quality television, at 1 mbps, to the IMAX motion picture format at just under 100 mbps.

Another way to read the Figure is to keep the communications capability fixed with time and let the number of spacecraft grow to reach the value shown by the curves. Even using the conservative (lower) curves, the factor of 100 discussed in the Introduction can be achieved before the year 2015 in all cases.

The use of advanced communications techniques on the Galileo spacecraft has resulted in their acceptance on future deep space missions and has indicated a path toward increasing the communications efficiency for deep space by a factor of 100. This will allow NASA and the world deep space community to support a very aggressive exploration program with as many as 12 launches each year.

Dr. Les Deutsch is currently the Chief Architect of JPL's Telecommunications and Mission Operations Directorate. Dr. Deutsch has previously managed the Deep Space Network's Technology Development Program and JPL's Communication Systems Research Section. He received the IEEE Judith Resnick medal in 1991 for "contributions to the theory and practice of deep-space communications and information processing." Dr. Deutsch holds over 25 patents in the fields of communications and electronic music. He has a Ph.D. in Mathematics from Caltech where he also serves as University Organist.

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