NEW TRACKING IMPLEMENTATION IN THE DEEP SPACE NETWORK

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ABSTRACT

As part of the Network Simplification Project, the tracking system of the Deep Space Network is being upgraded. This upgrade replaces the discrete logic sequential ranging system with a system that is based on commercial Digital Signal Processor boards. The new implementation allows both sequential and pseudo-noise types of ranging.

The other major change is a modernization of the data formatting. Previously, there were several types of interfaces, delivering both intermediate data and processed data (called "observables"). All of these interfaces were bit-packed blocks, which did not allow for easy expansion, and many of these interfaces required knowledge of the specific hardware implementations. The new interface supports four classes of data: raw (direct from the measuring equipment), derived (the observable data), interferometric (multiple antenna measurements), and filtered (data whose values depend on multiple measurements). All of the measurements are reported at the sky frequency or phase level, so that no knowledge of the actual hardware is required. The data is formatted into Standard Formatted Data Units, as defined by the Consultative Committee for Space Data Systems, so that expansion and cross-center usage is greatly enhanced.

1.0 INTRODUCTION

The Deep Space Network (DSN) is in the process of upgrading its uplink and downlink equipment for its 34 meter and 70 meter antenna subnets. The DSN is part of the Deep Space Mission System (DSMS), which also contains 11m and 26m antenna subnets. The task, known as the Network Simplification Project (NSP), is modernizing many functions and consolidating the control of the major elements of the uplink and downlink [1]. As part of this modernization, the old sequential ranging and tracking data reporting systems are being replaced.

Another major element of the NSP is modernizing the tracking data delivery format. Currently, there are several interfaces that a project must use to obtain intermediate data and processed data (called "observables"), which are used for determining the trajectory solutions. These old interfaces were designed in an era when "every bit counted" and use non-obvious scaling and bit packing to get the most data compression. It is very difficult to update these interfaces for new features (such as new RF bands) and new hardware. They also contribute to errors when the measurement does not fit into the fixed number of bits, and require the end user of the data to have knowledge of the implementation of the tracking hardware. The new interface will eliminate these problems. It also formats the data into Standard Formatted Data Units, as defined by the Consultative Committee for Space Data Systems (CCSDS), so that expansion and cross-center usage is greatly enhanced.

This paper is divided into three parts. First, we discuss the current tracking system. Next, we present the upgraded system that will be in operation by June of 2003. Finally, we discuss the new tracking data interface is some detail.

2.0 EVOLUTION OF THE DSN TRACKING SYSTEM

Tracking data comes in two flavors, Doppler and ranging measurements. A Doppler measurement provides the change in the frequency of the received carrier from the spacecraft, which is related to the velocity of the spacecraft. Ranging is a measurement of the round-trip light time (RTLT) to the spacecraft, which provides the distance to the spacecraft. Navigators use both types of measurements to compute the spacecraft trajectory. Raw measurements made at the station are processed back at JPL into a measurement delivered to the navigators, called the "observable". The exact definition of the observable for ranging and Doppler is provided in [2]. Currently all tracking data from the DSN is reported from the Metric Data Assembly (MDA). Data from the DSN near-Earth tracking 26 meter and 11 meter subnets is reported from other subsystems using interfaces similar to the MDA interface.

2.1 Doppler

The primary measurement that the MDA reports is called the "Doppler count", or "cycle count". As explained below, the original downconversion process produced a Doppler count that was the phase measurements of a true Doppler frequency. The Doppler Extractor (DE) hardware included multipliers that matched the turnaround ratios used onboard the spacecraft. Historically, there were standard, agreed-upon turnaround ratios between each uplink frequency band and downlink frequency band. This is no longer the case for the new Ka-band downlink spacecraft. However, the MDA interface and Radio Metric Data Conditioning (RMDC) processing at JPL rely on the assumption that the downlink band uniquely determines the turnaround ratio used in the downconversion process. This requires customers to have knowledge of the downconverter process to correct the "Doppler observable" or convert back to sky level.

Another feature of the MDA interface is the periodic rollover of the "1MHz biased Doppler observable" cycle counts. The old MDA frequency counters produced a monotonically increasing cycle count that grew at approximately 10^6 cycles every second. The MDA software removes cycle count rollovers created by the hardware reaching the limit of the counter's resolution. However, the MDA interface causes a rollover effect in the output data. The high-rate (10 per second) Doppler data type reports the cycle count on the second mark modulo 2^{32} (rollovers approximately every 4294 seconds) and the other nine cycle counts modulo 2^{19} (rollovers approximately every 0.52 seconds).

The Block V era digital receivers and exciters report carrier phase to the MDA report at sky level. This has proven to be a viable and generic way of reporting carrier information. During the Block V era, the creation of a "true Doppler" ceased to exist, but the "Doppler count" usage was continued.

2.2 Ranging

Ranging is done in three steps. First, the uplink carrier is modulated with a ranging signal. Second, the spacecraft transponder locks to the carrier, demodulates and filters the ranging signal, and then re-modulates it onto the coherent downlink carrier. Finally, the downlink receiver locks to the carrier, demodulates the ranging signal and correlates it with a copy of what was originally transmitted. The ranging signal is frequency coherent with the uplink carrier, so that the Doppler shifts it experiences can be removed using a signal coherent with the downlink carrier. Because the uplink carrier may be tuned (ramped), the ranging measurement is made in units that are directly related to the period of the carrier, called Range Units (RU). By convention, 1 RU is the length of 2 cycles of the uplink carrier frequency expressed at the S-band uplink level. In time domain, a range unit is approximately 1 nsec. When converting range in RU into distance in meters, the time-varying size of 1 RU is obtaining by using the uplink ramp data.

The current Sequential Ranging Assembly (SRA) is the only ranging capability for deep space applications. Sequential ranging derives its name from the fact that the ranging modulation is a series of square wave tones that are sent one after another. The first tone (the clock component) is the highest frequency of the sequence. Since ranging resolution is quantized to a fraction of a tone cycle, this component sets the absolute accuracy of the measurement. The lower frequency tones are used to resolve the ambiguity of the measurement. The clock component is typically about 1 MHz. The SRA ranging measurement has a resolution of one RU, but the accuracy depends on the ranging SNR, calibration measurements, and systematic error sources. With sufficient power, ranging accuracy of a few meters can be realized.

The ranging observable used by navigation specifies the round trip range (to an ambiguity determined by the number of components used) from the phase center of the antenna to the spacecraft. To produce this, the ranging measurement must be corrected for several items. First, the delay of the range signal in the uplink and downlink cables and equipment must be measured and removed. This delay is measured during the pre-track ranging calibration activity. Secondly, the delay in the system to the antenna phase center that is not included in the calibration must be accounted for. Finally, the delay in the spacecraft transponder and antenna system must be removed. These last two delays are fixed and are subtracted back at RMDC when the observable is computed.

The SRA is connected to both the uplink and downlink equipment. This situation is undesirable if sharing of downlink equipment between antennas is required (as it is for future tracking scenarios).

2.3 User Interfaces

There are three different types of interfaces for the user to currently get their tracking data. Their names come from the module number in the [3]. Specifically, they are TRK-2-15A, TRK-2-18, and TRK-2-25. All three are bit-packed interfaces, using variable length integers to represent all values, both integer and floating point. All interfaces are historical in the sense that they do not necessarily use measurements at sky level. Most measurements are reported at the original hardware implementation levels, so to reconstruct the measurement, a user needs to know how the hardware works. Also, the bit packing limits the precision and accuracy of the measurement.

TRK-2-15A data is the raw measurement data from the MDA that is sent in real time. While it is truly an internal interface (between two DSMS assemblies), it has been provided as a data interface to external users. Over the years, this has greatly limited the capability to adjust to new features in the tracking system, since a change requires approval of all external customers, which is a difficult task.

TRK-2-25 data is an archival format of the raw data (TRK-2-15A, and 26 meter and 11meter subnet data). The main use of it, besides internal RMDC usage, is for providing Doppler and range measurements to Radio Science users.

TRK-2-18 is the main interface to navigators. It provides the observable data, which is the result of processing the raw data. The main drawback with this interface (besides the rigid formatting) is that there is limited configuration and performance data associated with the measurements, so it is hard to qualify some of the results.

2.4 Evolutionary Steps

The architecture of the hardware implementation in the DSN drove how the data was collected and reported. The exciter provides the uplink carrier generation and accepts modulation for ranging and commanding purposes. The receiver tracks the carrier transmitted by the spacecraft and demodulates the telemetry and ranging signals. An early architecture is shown in Fig. 1. The details of the interface protocols, formats, and content were driven by small design changes implemented over time. Each step involved compromise and tradeoffs, resulting in a tracking system that works but is not optimal. Below is a rough chronological overview of the steps that led to the current DSN tracking system implementation.

2.4.1 Near the beginning: True Doppler

Early in the DSN history, a receiver and exciter were parts of one subsystem with shared hardware. The uplink carrier could be ramped manually to 'tune-in' to the spacecraft at the start of the pass. This tuning assists the spacecraft Phase Locked Loop (PLL) in acquiring the carrier from the ground. After the 'tune-in', the uplink carrier was set to a constant frequency for the rest of the spacecraft pass. The DE mixed a scaled copy of the transmitted uplink carrier with a scaled copy of the received carrier, then mixed the resulting Doppler frequency with a 1 MHz tone. The resulting positive frequency was measured with a frequency counter in the MDA. This frequency is called the "1MHz biased Doppler observable". The JPL Navigation computations subtracted 1MHz from the "observable" and assumed the remainder was the true Doppler frequency. The MDA packaged the raw "observable" cycle counts, some configuration items, and real-time residual metrics in the bit-packed TRK-2-15 interface records. The tracking data sent to JPL was validated, pre-processed, and archived for distribution by the RMDC subsystem before being sent to the JPL navigation teams.

2.4.2 Ramped Uplink

The DSN added the capability to ramp the uplink carrier continuously to reduce the strain on the spacecraft PLL during the tracking pass (due to Doppler shifts). This also provided a computer-controlled spacecraft 'tune-in' capability, eliminating the problems associated with manual tuning. The ramping was done by a Digitally Controlled Oscillator (DCO) which was controlled from the MDA. The two reasons for controlling this uplink carrier function from the MDA were: the uplink ramp frequencies had to be reported to Navigation and only the MDA had a Navigation interface; and at the time, the MDA processor had more available programmable memory than the receiver/exciter did.

The DSN also added the capability to downconvert the received carrier frequency with a simulation synthesizer frequency unrelated to the uplink carrier. This enabled the production of an "observable" during tracking passes that are 1-way (no uplink carrier), 2-way noncoherent (spacecraft is locked to the uplink carrier, but is generating the downlink carrier separately), and 3-way (spacecraft is locked to the uplink carrier from one ground station and is generating the downlink carrier coherently from the uplink, but is received at another ground station).

When the new ramping or simulation synthesizer capabilities are used, the "observable" minus 1 MHz is no longer the true Doppler frequency. The DE uses the currently transmitted uplink carrier (or simulation synthesizer), which is not

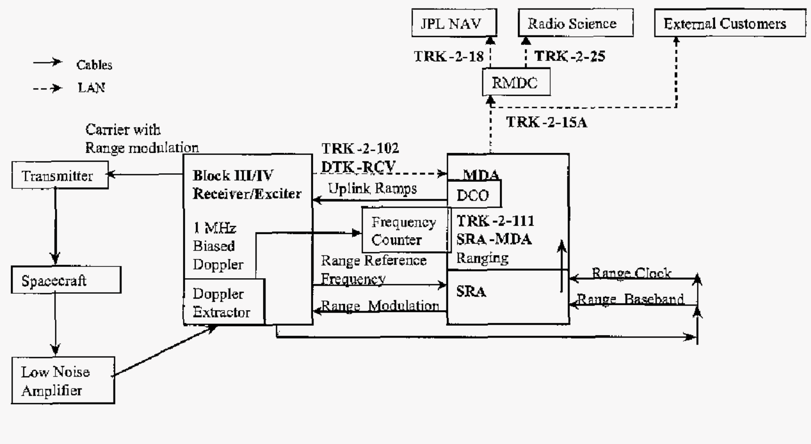

Fig. 1. Early DSN Tracking Architecture

the same as the actual uplink carrier transmitted an RTLT before. The RMDC and JPL Navigation computations were increased in complexity to correct the "observable" using knowledge of the hardware downconversion process. Items were added to the TRK-2-15 to report the changing uplink carrier frequency. This uplink ramp data type is reported at the DCO level of 44 MHz, before the hardware upconverts to transmitted sky level. The upconversion for S-band and X-band used completely different hardware implementations, which was reflected in the RMDC calculations.

2.4.3 Ranging Data

Ranging capabilities have been part of the DSN since near the beginning, culminating in the SRA. The MDA controls the SRA, and outputs the ranging data to navigation. More data types and items for ranging and DRVID (Differenced Range Versus Integrated Doppler) were added to the TRK-2-15 when the SRA was implemented in the DSN.

2.4.4 A New MDA with Old Interfaces

In the early 1990's the Signal Processing Center (SPC) upgrade provided a new MDA platform. However, only minimal changes were allowed in the output interface due to inertia of the customers' subsystems. Several of the customers getting the TRK-2-15 did not have the money or schedule to update to a new interface. The new MDA was designed to produce a TRK-2-15A output interface that is still bit-packed and is almost identical to the TRK-2-15, except for a new "Allan Variance" data type.

2.4.5 The Block V Era

The DSN migrated to Block V Receivers and Block V Exciters in the mid 1990's. The main differences are:

1. The new receiver and exciter are based on digital implementations that allow more control over the process.
2. For the first time, the receivers are physically separated from the exciter hardware, with separate controllers.
3. There is no Doppler Extractor because the Block V Receiver directly measures an intermediate frequency independent of the uplink. The Block V Receiver also reports the received carrier frequencies at sky level.
4. The tuning of the uplink carrier is controlled and done by the Block V Exciter, making the DCO obsolete. The Block V Exciter reports the uplink carrier frequencies at sky level.

Fig. 2 shows the Block V architecture of the tracking system. To ease the Block V implementation and to provide a transition from the earlier, joined receiver/exciters, the MDA was modified to accept Block V Receiver and Block V Exciter data. The customers mandated that the MDA continue to report data using the TRK-2-15A interface during the transition period. To support this, the MDA software downconverts the Block V Exciter reports to the 44 MHz level and separately downconverts the Block V Receiver data from sky level to a "1MHz biased Doppler observable" using a fake simulation synthesizer frequency. All data is still reported in the TRK-2-15A.

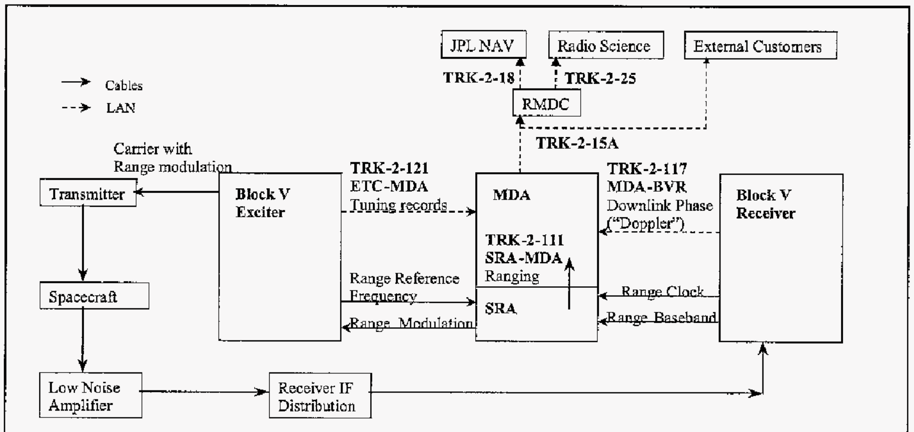

Fig. 2. Current DSN Tracking

2.1.6 Current Tracking System

The transition to the Block V Receivers and Block V Exciters was completed. However, the MDA continues to take in the sky level tracking data from these subsystems and report it at the old hardware levels of 44 MHz and "1MHz biased Doppler observable". This continues even though the MDA Frequency Counters and DCO's that established these hardware levels no longer exist in the DSN. Also, JPL Navigation processing routinely converts the TRK-2-15A data back to the sky level frequencies originally produced by the Block V equipment. Several errors and limitations due to the MDA downconversion and RMDC re-construction, and to the bit-packing of the interface have been identified. Despite known workarounds, these errors continue to occur intermittently.

3.0 NEW TRACKING SYSTEM

The DSN Network Simplification Project, NSP, will consolidate several subsystem control functions in uplink and downlink subsystems, resulting in a smaller number of subsystems and interfaces [1]. Fewer subsystems will reduce maintenance and simplify the configuration and control of everyday tracking functions. The NSP also provides a new ranging hardware implementation. The MDA and SRA will be phased out and the TRK-2-15A interface will be retired. New tracking data interfaces are designed to address several of the problems encountered with the previous interfaces. The NSP tracking system has several differences from the current tracking system.

The NSP consolidates uplink functions into the Consolidated Uplink Controller (UPL) subsystem. The UPL functions consist of carrier generation, ranging modulation, and command generation (not part of the tracking system). The downlink functions are consolidated into the Downlink Tracking and Telemetry (DTT) subsystem. A DTT channel contains carrier tracking, telemetry processing (not part of the tracking system), and ranging correlation.

Each UPL and each DTT channel will report carrier and ranging tracking data. The subsystems that perform the tracking measurements will report the tracking data to JPL, instead of passing it to a 'middleman' MDA subsystem. At JPL, the RMDC is replaced by the Tracking Data Delivery Subsystem (TDDS). Fig. 3 shows the new configuration.

The raw data is reported at the level used in the DSN hardware. Since DSN subsystems are now configured at sky level, display data at sky level, and handle the data internally at sky level; the new interface will report at sky level. There is no DE and no real Doppler frequency, so "Doppler data" will be replaced by Carrier data. "Doppler observables" will be generated back at TDDS. Since the carrier data is reported at its natural RF level, no hardware specific knowledge is required once it leaves the station.

The SRA will be replaced with new ranging hardware contained within the UPL and DTT subsystems. The SRA, which is based on custom wire-wrap boards is replaced by commercial VME boards using TI Digital Signal Processors (DSPs) [4]. The speed of the commercial technology allows for the software to read the data in at 16 MHz and perform all of the integrations and correlations needed to generate the ranging measurement, without custom hardware (other than an interface board to get the data into the processor board).

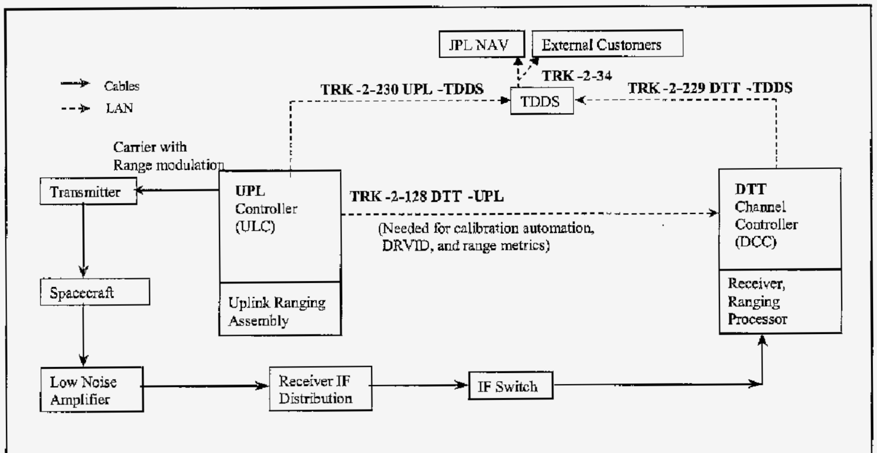

Fig. 3. The NSP Tracking System

The SRA design requires that it be hardwired to a receiver and an exciter. However, the receivers can now be connected to any antenna, due to the addition of an IF switch. This required a new ranging design where the downlink ranging correlation process could be separated from the uplink ranging modulation process.

The ranging function is split into two processor boards, one which generates the ranging modulation for the uplink and the other which correlates the received ranging signal with a local model. Ranging phase (phase of the ranging signal relative to a time-tag) is measured both on the uplink and downlink side. The measurements are sent to TDDS, where they are differenced to generate the range measurement (the differencing is also done by the downlink to provided the operators with metrics on the range measurement). Implementing the ranging this way provides three improvements:

1. The uplink and downlink hardware are no longer tied together by the ranging function. Any downlink can be connected to any antenna, creating a pool of downlink processors.
2. The operation is simpler, since the uplink is concerned only with uplink ranging and the downlink with downlink ranging; three-way measurements become much simpler.
3. Because the ranging signal is generated in software, the system can easily add new types of ranging. As part of the NSP, pseudo-noise (PN) ranging is being added.

The interface problems are also addressed. As mentioned above, all interfaces are at their natural level. Additionally, the interfaces between Uplink and TDDS and Downlink and TDDS are considered internal interfaces; no external users receive the data transmission. This will allow the interface to change with time, as new capabilities are added, without the complication of involving outside users. External users will all receive the tracking data in a new format, which is discussed in the next section. The TRK-2-18 interface will continue to be made available to users for a period of time.

4.0 NEW TRACKING INTERFACE

The new external tracking interface (dubbed "TRK-2-34" due to its module number in [3]) addresses the problems with the older interfaces by using standards that have been accepted by the international community. Instead of representing numbers in a bit-packed, split format implementation, standard data formats are used (8-bit integers, 16-bit integers, and 32-bit integers, both signed and unsigned; IEEE standard [5] single precision and double precision floating point numbers). Additionally, the data packing technique is based on the CCSDS Standard Data Format Unit (SFDU) recommendation [6]. Some of the data types in the TRK-2-34 do not come from the UPL or DTT subsystems, but they are included so that JPL can have a single external tracking interface that covers all known types of tracking data.

Instead of requiring the recipient to have detailed knowledge of the system implementation, all data is presented in the natural units. Carrier measurements are at sky frequencies and phase, and ranging measurements are in Range Units. This allows different types of uplink and downlink equipment to be used, without the user needing to know the type of equipment used. For example, although the new tracking equipment is being implemented in the 34 meter and 70 meter subnets of the DSN, the equipment at the 26 meter antennas will not change. Users subscribing to the TRK-2-34 interface will be able to process the output data without needing to know what type of antenna was used. However, due to the peculiarities of the other antennas (26m and 11m subnets), there are data blocks devoted solely to their data.

A principal design goal of the new interface was to include key configuration data along with the measurements. Too often, measurements are deemed unreliable because the equipment configuration was not available. TRK-2-34 includes the pertinent configuration (e.g., loop bandwidth) and performance data (e.g., various signal-to-noise ratios, etc.) that allows a user to have confidence in the measurement (or explain why the measurement is invalid).

The TRK-2-34 interface provides four types of data measurements: Raw data, which is the raw measurements from the new tracking equipment (either UPL or DTT); Derived data, which are the observables derived from the raw measurements; Interferometric data, which are the results of Very Long Baseline Interferometry (VLBI) measurements; and Filtered data, which are measurements that are generated from multiple raw data measurements.

The tracking data SFDU implementation uses the concept of the label-value-object (LVO). An LVO is a data structure that is comprised of a label field and a value field. The label field provides for the data structure to be self-identifying and self-delimiting. The value field contains user-defined data in any format. These components are discussed below.

4.1 Header Fields

The TRK-2-34 has are three main fields of header data. The *label field* identifies the tracking data type and the length of the SFDU block. The *primary header* contains fields indicating the length of the primary header, the mission identifier, the SFDU type, and the tracking data type. The *secondary header* provides configuration and status data for the data blocks. The items in the *secondary header* were selected based on the type of information a customer will want for sorting the data. The customer can sort on RF band, carrier lock status, or transmitter on/off status without having to examine the entire data block. There are eighteen types of data blocks, which are described in detail below. There are five types of *secondary headers*, organized into the following types:

Uplink data:	Uplink Carrier Phase, Uplink Sequential Ranging Phase, Uplink PN Ranging Phase, and Ramps.
Downlink data:	Downlink Carrier Phase, Downlink Sequential Ranging Phase, and Downlink PN Ranging Phase.
Derived data:	Doppler, Sequential Range, Angles, DRVID, PN Range, Tone Range, Carrier Observable, and Total Phase Observable.
Interferometric data:	VLBI.
Filtered data:	Smoothed Noise and Allan Deviation.

Uplink data are the raw uplink phases from the 34m and 70m antennas and the uplink ramps. Downlink data are the raw downlink phases from the 34m and 70m antennas. Derived data are the data from the 11m and 26m antennas, and the processed doppler, carrier, range and DRVID data from the 34m and 70m antennas. Interferometric data are the VLBI data. Filtered data are the measurements derived from the previous data (smoothed noise and Allan Deviation).

4.2 Data Blocks

There are four data types with Uplink Data secondary headers. The *Uplink Carrier Phase* is the raw transmitted carrier phase measurement. It is a new type of data coming from the UPL. This includes ramp frequency, ramp rate, and transmitter output power. The *Uplink Sequential Ranging Phase* is the raw transmitted sequential ranging phase and is also a new data type from the UPL. It includes ranging configuration items which are useful for cross-checking before combining it with the downlink ranging phase. The *Uplink PN Ranging Phase* is the raw transmitted PN ranging phase. It is a new data type from the UPL similar to the uplink sequential ranging phase, but for PN type ranging. Lastly, the *Ramp* data is a minimal set of uplink tuning data. It is generated by filtering the Uplink Carrier Phase data stream for changes in status or tuning frequency. The *Ramp* data is very much like the old TRK-2-15A ramp data type, but converted to sky level and including carrier phase counts.

There are three data types with Downlink Data secondary headers. The *Downlink Carrier Phase* is the raw received carrier phase measurement. The *Downlink Sequential Ranging Phase* is the raw received sequential ranging phase. And the *Downlink PN Ranging Phase* is the raw received PN ranging phase. All of these are new data types from a DTT channel. Each contains configuration, power level, and residual information as well.

There are eight data types with Derived Data secondary headers. The *Doppler* data is created by TDDS to be very similar to the old TRK-2-15A Doppler count data, except that it is not bit packed. Similarly, the *Sequential Range* data is the sequential range measurement, including both the raw measurement (uplink ranging phase minus downlink ranging phase) and the ranging observable, which includes the compensation for station and spacecraft delays. The *Angle* data is the angle data from the 26 meter antennas and is used to determine how the antenna was pointed. The *DRVID* data contains the DRVID measurement, derived from the range measurement and the Doppler measurement. It is used for media characterization. The *PN Range* data is the PN range measurement, containing both the raw measurement (uplink ranging phase minus downlink ranging phase) and the ranging observable, which includes the compensation for station and spacecraft delays. The *Tone Range* data is the tone ranging measurement only available at the 26 meter subnets; it includes both the raw measurement (uplink ranging phase minus downlink ranging phase) and the ranging observable, which includes the compensation for station and spacecraft delays. The *Carrier Observable* data is the carrier observable measurement at sky level. The carrier observable is the change in the received carrier phase over the time period specified. The block contains a variable number (selected by the user) of measurements. The *Total Phase Observable* data is the total phase observable measurement determined by integrating the carrier phase over the time period specified. The block contains a variable number (selected by the user) of measurements.

There is only one data type with an Interferometric Data secondary header. The *VLBI* data is the VLBI observable measurement. VLBI measurements are differential measurements of the range and Doppler, produced by two stations, at different complexes, observing the non-coherent spacecraft signal at the same time.

There are two data types with Filtered Data secondary headers. The *Smoothed Noise* data is the standard deviation of the detrended downlink frequency residuals. The detrending is the removal of the least squares linear fit of the frequency residuals over the sample period. The *Allan Deviation* data is the Allan deviation measurement of the downlink carrier. Allan deviation is computed for interval (τ) values of 0.1, 1, 10, 100, and 1000 seconds. The frequency residuals are used for the computation (to remove the known motion effects, such as earth rotation).

5.0 CONCLUSION

A new tracking system implementation has been discussed. Obsolete equipment is being replaced, trading custom hardware for commercial processors and specialized software. Non-standard interfaces based on hardware built up to 30 years ago are being replaced by interfaces that report data in its natural units, using standardized formats. This change will be complete by June, 2003.

6.0 REFERENCES

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