DSN Telecommunications Link
Design Handbook

209, Rev. A
Open-Loop Radio Science

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Change Log

Rev	Issue Date	Affected Paragraphs	Change Summary
Initial	1/15/2001	All	All
A	6/1/2010	All	Added Wideband VLBI Science Receiver (WVSR) and VLBI Science Receiver (VSR). Eliminated the Rev. E designation for the document series.

Note to Readers

The 810-005 document series has been structured so that each document module can be independently revised without affecting others in the series. Hence, the Revision E previously designated for 810-005 has become unnecessary. This module is one of the many in the 810-005 series; each may be published or changed, starting as an initial issue that has no revision letter. When a module is updated, a change letter is appended to the module number in the header and a summary of the changes is entered in the module's change log.

This module documents the Radio Science Receivers that became operational in the year 2001, the VLBI Science Receiver (VSR) operational since 2002, and the Wideband VLBI Science Receivers (WVSR) operational since 2007.

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1 Introduction

1.1 Purpose

This module describes the capabilities and performance of the Deep Space Network (DSN) Open-loop Radio Science equipment used for supporting radio science (RS) experiments.

1.2 Scope

This module discusses the open-loop radio science receiving equipment functions, architecture, operation, and performance. Although some RS experiments require uplink support and closed-loop Doppler and ranging data, this module only describes the open-loop recording capability that is used during radio science experiments. Open-loop recording is carried out by the Radio Science Receivers (RSR), the Very-Long Baseline Interferometry (VLBI) Science Receivers (VSR), or the Wideband VSR (WVSR). Details of the closed-loop Doppler tracking system can be found in module 203, 34-m and 70-m Receiver Doppler. Details of the uplink functions can be found in the 70-m, the 34-m High Efficiency (HEF), and the 34-m Beam Waveguide (BWG) telecommunications interface modules 101, 103, and 104 respectively.

2 General Information

Radio science experiments involve measurements of small changes in the phase, frequency, amplitude, and polarization of the radio signal propagating from an interplanetary spacecraft to an Earth receiving station. By properly analyzing these data, investigators can infer characteristic properties of the atmosphere, ionosphere, and planetary rings of planets and satellites, measure gravitational fields and ephemeredes of planets, monitor the solar plasma and magnetic fields activities, and test aspects of the theory of general relativity. Details of Radio Science System applications may be found in the JPL Publication 80-93, Rev. 1, written by S.W.

Asmar and N.A. Renzetti, titled: *The Deep Space Network as an Instrument for Radio Science Research*. The term RS receiver will be used to designate RSR, VSR, and WVSR.

2.1 Functions

The functions of the DSN with respect to conducting radio science experiments can be summarized as follows:

- Providing uplink carrier signals to the spacecraft with a pure spectrum, including low phase noise and stable frequency.
- Acquisition, down conversion, digitization, and recording of the downlink carrier with minimal degradation to its frequency, phase, amplitude stability, and polarization.
- Assuring that the expected signals are being acquired and recorded.

2.2 Hardware Configuration

All radio science experiments require use of the antenna, microwave, antenna-mounted receiving equipment, and frequency and timing equipment at the stations, as well as the receivers in the SPC. They also require the Ground Communications Network (GCN) to deliver data from the stations to users at JPL, where experiments are monitored. DSN stations are designed to meet radio science requirements for stability. However, one of the beam waveguide stations at the Goldstone Deep Space Communications Complex (DSCC), DSS 24, is not equipped with a high-quality frequency distribution system and is not recommended for radio science applications. A block diagram of the open-loop radio science receiving capability is shown in Figure 1.

The receiving equipment on each DSN antenna produces one or more intermediate frequency (IF) signals with a nominal center frequency of 300 MHz and a bandwidth that depends on the microwave and low noise amplifier equipment on the antenna as described in modules 101, 103, and 104. These IF signals are routed to a distribution amplifier (not shown in Figure 1) that provides multiple copies of each signal for use by the RS receivers, the telemetry and tracking receivers, and other equipment in the signal processing center (SPC). One copy of each signal is provided to the Full Spectrum Processing (FSP) IF Switch equipment, which further divides and amplifies it in such a way that any of the RS receiver channels can be connected to any antenna IF signal.

Each RS receiver contains two channels. The design of the system software is such that, from the user's viewpoint, each channel can be considered as an independent open-loop receiver.

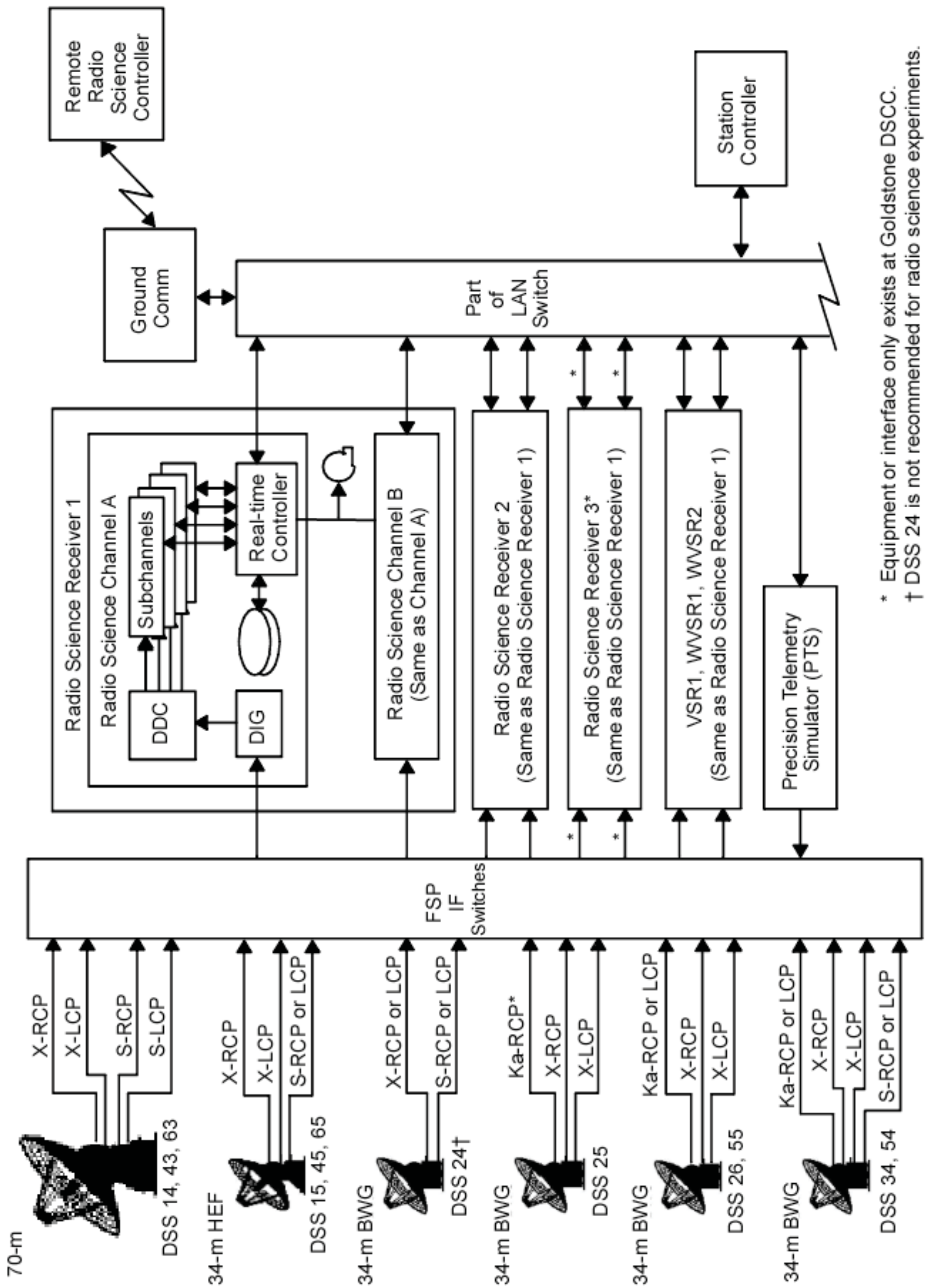

Figure 1. Radio Science Receiving Equipment Configuration

2.3 RS Receiver Signal Processing

The IF signal is fed to the Digitizer (DIG) where it is filtered to limit its bandwidth to the range of 265–375 MHz for the RSR and VSR, and 10 to 630 MHz for the WVSR, all centered at 320 MHz. This corresponds to a received frequency range for the RSR and VSR of 2,265–2,375 MHz at S-band, 8,365–8,475 MHz at X-band, and 31,965–32,075 MHz at Ka-band. For the WVSR, the received frequency range is 2,010-2,630 MHz at S-band, 8,110-8,730 MHz at X-band, and 31,710-32,330 MHz at Ka-band. However, the actual received frequency range will depend on the characteristics of the equipment on the selected antenna.

On the RSR and VSR, the filtered signal is downconverted to a center frequency of 64 MHz and digitized at 256 Ms/s with an 8-bit resolution.

On the WVSR, the filtered signal, at a center frequency of 320 MHz, is digitized at 1280 Ms/s with an 8-bit resolution.

The resultant data are fed to the Digital Downconverter (DDC) that selects any 16 MHz bandwidth from the original bandpass with a resolution of 1 MHz and downconverts it to baseband in the form of a 16 Ms/s, 8-bit, complex data stream.

For the RSR, baseband processing provides up to four subchannel filters to select frequency bands of interest for recording. The number of available filters depends on the selected bandwidths that can be broadly categorized as Narrowband, Medium Band, or Wideband. The following selection of filters is available:

- 4 Narrowband
- 2 Narrowband and 1 Medium Band
- 2 Medium Band
- 1 Wideband

For the VSR and WVSR, there are up to four channels, each with 2 narrowband and 2 wideband subchannels.

The filters are specified by their bandwidths, the desired resolution (bits/sample) and an offset from the predicted sky frequency predict file. This frequency predicts file is created by the DSN network support function and contains the spacecraft frequency altered by spacecraft trajectory and Earth-rotation. Table 1 lists the supported filter bandwidths and resolutions and gives the resultant data rate for each combination for the RSR. Similarly, Table 2 is for the VSR and WVSR. Figure 2 shows the relationship between the frequency bands within the RSR and VSR. The WVSR is similar, except that the digitized band covers the frequency range 0-640 MHz. See Figure 3 for the relationship of frequency bands within the WVSR.

2.4 RS Receiver Signal Detection

Because the RS receiver is an open-loop receiver, it does not have a mechanism to align its passband to (establish lock with, or track) the received signal. Instead, it relies on predicts to position its passband. This creates a risk that a predict error might result in the wrong portion of the received spectrum being processed. To assist in recognizing this, the RS receiver analyzes the data in each subchannel and provides a detected signal indication on the main display for that subchannel for diagnostic purposes only.

In addition to the detected signal indication, the RS receiver provides a frequency-domain representation of the bandpass being recorded in each RS receiver subchannel using a Fast-Fourier Transform (FFT). Characteristics of the FFT such as number of points, averaging, and update rate are under user control.

Table 1. RSR Supported Bandwiths and Resolutions with Resulting Data Rate

Category	Bandwidth	Resolution (b/sample)	Data Rate (b/s)
Narrowband	1 kHz	16	32,000
	2 kHz	16	64,000
	4 kHz	16	128,000
	8 kHz	16	256,000
	16 kHz	16	512,000
	25 kHz	16	800,000
	50 kHz	16	1,600,000
	100 kHz	16	3,200,000
	1 kHz	8	16,000
	2 kHz	8	32,000
	4 kHz	8	64,000
	8 kHz	8	128,000
	16 kHz	8	256,000
	25 kHz	8	400,000
	50 kHz	8	800,000
	100 kHz	8	1,600,000
Medium Band	250 kHz	16	8,000,000
	500 kHz	16	16,000,000
	250 kHz	8	4,000,000
	500 kHz	8	8,000,000
	1 MHz	8	16,000,000
	250 kHz	4	2,000,000

Table 1. RSR Supported Bandwiths and Resolutions with Resulting Data Rate (Continued)

Category	Bandwidth	Resolution (b/sample)	Data Rate (b/s)
Medium Band (Continued)	500 kHz	4	4,000,000
	1 MHz	4	8,000,000
	2 MHz	4	16,000,000
	250 kHz	2	1,000,000
	500 kHz	2	2,000,000
	1 MHz	2	4,000,000
	2 MHz	2	8,000,000
	4 MHz	2	16,000,000
	250 kHz	1	500,000
	500 kHz	1	1,000,000
	1 MHz	1	2,000,000
	2 MHz	1	4,000,000
	4 MHz	1	8,000,000
Wideband	8 MHz	2	32,000,000
	8 MHz	1	16,000,000
	16 MHz	1	32,000,000

Table 2. VSR and WVSR Supported Bandwiths and Resolutions with Resulting Data Rate

Category	Bandwidth	Resolution (b/sample)	Data Rate (b/s)
Narrowband	1 kHz	16	32,000
	2 kHz	16	64,000
	4 kHz	16	128,000
	8 kHz	16	256,000
	16 kHz	16	512,000
	25 kHz	16	800,000
	50 kHz	16	1,600,000
	100 kHz	16	3,200,000
	1 kHz	8	16,000
	2 kHz	8	32,000
	4 kHz	8	64,000
	8 kHz	8	128,000
	16 kHz	8	256,000
	25 kHz	8	400,000
	50 kHz	8	800,000
	100 kHz	8	1,600,000
Wideband	1 MHz	8	16,000,000
	2 MHz	8	32,000,000
	1 MHz	4	8,000,000
	2 MHz	4	16,000,000
	4 MHz	4	32,000,000
	1 MHz	2	4,000,000
	2 MHz	2	8,000,000
	4 MHz	2	16,000,000
	8 MHz	2	32,000,000
	1 MHz	1	2,000,000
	2 MHz	1	4,000,000
	4 MHz	1	8,000,000
	8 MHz	1	16,000,000
	16 MHz	1	32,000,000

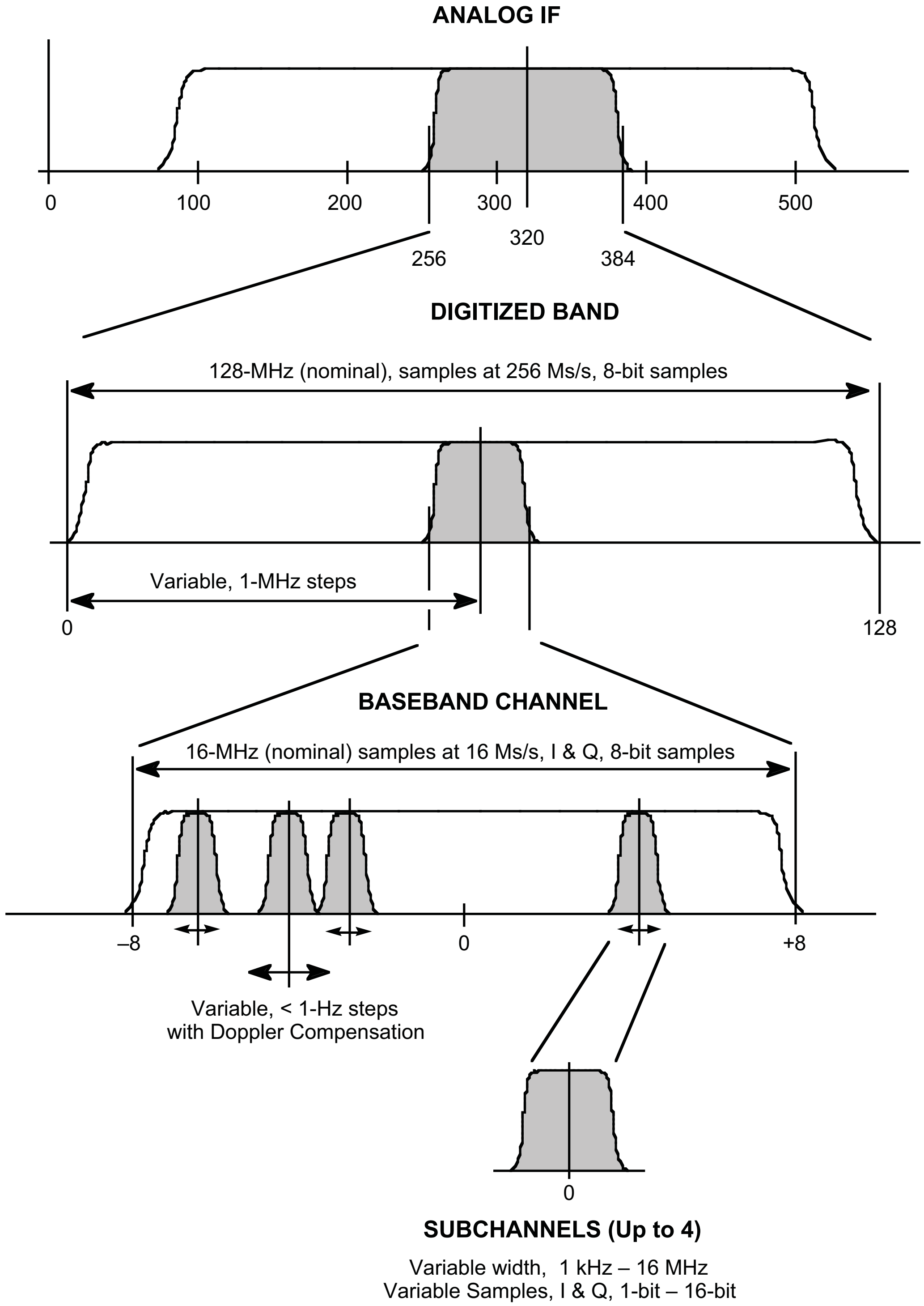

Figure 2. Relationships Between Processing Bands for RSR and VSR

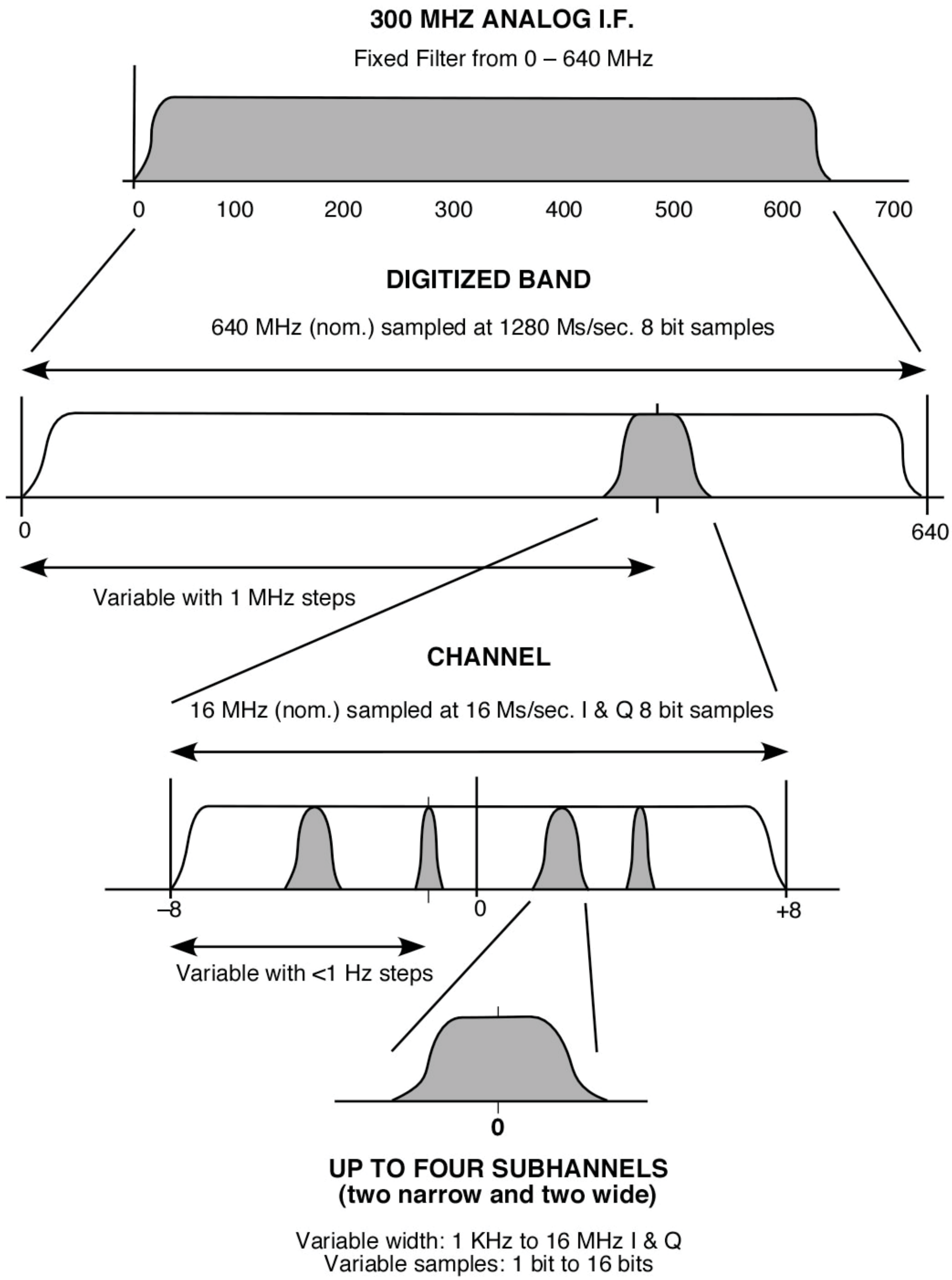

Figure 3. Relationships Between Processing Bands for WVSR

2.5 RS Receiver Operation

The radio science equipment operates in both a connection (link-assigned) and a stand-alone mode. In the connection mode, the Network Monitor and Control (NMC) function receives monitor data from the RS receiver for displays at the NMC and provides a workstation from which the RS receiver can be operated. RS receivers that are not assigned to a link may be operated in a stand-alone mode without interference to any activities in process at the complex. Monitor data is not forwarded to the NMC by RS receivers operating in the stand-alone mode.

The RS receiver employs a client-server architecture where each RS receiver acts as a server capable of accepting connections from up to five users operating the appropriate receiver client software at any time. In the link-assigned mode, one of these five clients is the NMC workstation. The RS receiver does not recognize any client as being superior to the others so it is up to the user to assign responsibility for control to one client with the other clients operating in a passive mode. One RS receiver client is required for each RS receiver being controlled or observed. Thus, a complex radio science experiment involving four RS receiver channels would require four RS receiver clients at the control point.

All functions of the RS receiver may be performed from the RS receiver client in real time. Of special interest to the RS experimenter is the ability to adjust (slew) the predicted frequency profile, to slew the individual subchannel frequencies, to adjust FFT parameters, and to enable or disable recording for each subchannel.

2.6 Data Delivery

When recording is enabled, baseband samples and ancillary information, discussed below, are formatted into a file of one-second data records and stored on disk drives for delivery to JPL or other users. A separate data file is created for each subchannel. Data delivery is normally via file transfer using Secure Shell (SSH) protocol. Data also may be obtained via File Transfer Protocol (FTP) or Digital Linear Tape (DLT) cartridges (applicable to RSR only). The RSR data format differs from that of the VSR and WVSR.

2.6.1 Ancillary Data

For the RSR, the following ancillary data are included as a header in each data record. A detailed description of the data is contained in DSN Document 820-013, module 0159 for the RSR, and module 0222 (to be released) for the VSR/WVSR. For the VSR and WVSR, only the first four items below are in the header of each data record. The users will need to include the last two items in the filename for each subchannel to properly identify the supporting station, tracking pass, and spacecraft.

- Data record version
- Receiver configuration
- Subchannel identification
- Time tag for first sample in block
- Station and pass identification
- Spacecraft identification

2.7 Performance

The principal characteristics of the RSR are summarized in Table 3. Table 4 presents the characteristics of the VSR and the WVSR. In addition, radio science experiments are influenced by the overall stability of equipment at the stations. The following sections provide information on performance characterization in terms of frequency stability, phase noise, and amplitude stability for the ground stations.

Table 3. Radio Science Receiver Characteristics

Parameter	Value	Remarks
Number of Channels		Note: Any channel may be connected to any received spectrum
Goldstone	6	
Canberra and Madrid	4	
Frequency Ranges Covered		
At RSR Input (MHz)	265 – 375	
Referenced to L-band (MHz)	1,645 – 1,755	L-band receive capability at 70-m subnet is 1,628–1,708 MHz
Referenced to S-band (MHz)	2,265 – 2,375	S-band downlink allocation is 2,200–2,290 MHz for Earth orbiter application and 2,290–2,300 MHz for deep space applications
Referenced to X-band (MHz)	8,365 – 8,475	X-band downlink allocation is 8,400–8,450 MHz for deep space application and 8,450–8,500 MHz for Earth orbiter applications
Referenced to Ka-band (MHz)	31,965 – 32,075	Ka-band downlink allocation is 31,800–32,300 MHz for deep space application and 25,500–27,000 MHz for Earth orbiter applications
IF Attenuation		
Range (dB)	0 – 31.5	
Resolution (dB)	0.5	

Table 3. Radio Science Receiver Characteristics (Continued)

Parameter	Value	Remarks
Doppler Compensation		
Maximum Doppler Shift (km/s)	30	At all downlink frequencies
Maximum Doppler Rate (m/s^2)	17	At all downlink frequencies
Maximum Doppler Acceleration (m/s^3)	0.3	At all downlink frequencies
Maximum Tuning Error (Hz)	0.5	At all downlink frequencies
Manual Offset (MHz)	–8.0 to +8.0	
Baseband Bandwidth (MHz)	16	
Baseband Resolution (MHz)	1	Positioning of baseband within IF or RF bandwidth
Number of Subchannels Available for each RSR	1 – 4	Configuration depends on data volume.
Subchannel Tuning		
Tuning (MHz)	±8	From center of baseband
Resolution (Hz)	<1	
Recording Bandwidths		See Table 1 for exact values.
Narrowband (NB), kHz	1 – 100	1 – 4-subchannels
Medium Band (MB), kHz	250 – 4,000	2 or 1 with 2 NB subchannels
Wideband (WB), MHz	8 or 16	NB and MB subchannels are not available
Resolutions (bits/sample)	16 – 1	Depends on selected bandwidth. See Table 1 for available resolutions.
Time Tagging		
Resolution (s)	1	
Accuracy (μs)	1	With respect to station clock
Signal Detection Display		1 for each subchannel being recorded
Number of points in FFT	100 – 4096	Default is 100
Spectra Averaging	1 – 100	Default is 10
FFT Interval (s)	1 – 10,000	Default is 10

Table 4. VLBI and Wideband VLBI Science Receiver Characteristics

Parameter	Value	Remarks
Number of Channels		Note: Any channel may be connected to any received spectrum
VSR	2	1 VSR, 2 channels each at each DSCC
WVSR	4	2 WVSR, 2 channels each at each DSCC
Frequency Ranges Covered		
At VSR Input (MHz) At WVSR Input (MHz)	265 - 375 10 - 630	
Referenced to S-band (MHz)	2,265 – 2,375 (VSR) 2010 – 2630 (WVSR)	S-band downlink allocation is 2,200–2,290 MHz for Earth orbiter application and 2,290–2,300 MHz for deep space applications
Referenced to X-band (MHz)	8,365 – 8,475 (VSR) 8,110 – 8,730(WVSR)	X-band downlink allocation is 8,400–8,450 MHz for deep space application and 8,450–8,500 MHz for Earth orbiter applications
Referenced to Ka-band (MHz)	31,965 – 32,075 (VSR) 31,710 – 32,330 (WVSR)	Ka-band downlink allocation is 31,800–32,300 MHz for deep space application and 25,500–27,000 MHz for Earth orbiter applications
IF Attenuation		
Range (dB)	0 – 31.0	
Resolution (dB)	1.0	
Doppler Compensation		
Maximum Doppler Shift (km/s)	30	At all downlink frequencies
Maximum Doppler Rate (m/s^2)	17	At all downlink frequencies
Maximum Doppler Acceleration (m/s^3)	0.3	At all downlink frequencies
Maximum Tuning Error (Hz)	0.5	At all downlink frequencies
Manual Offset (MHz)	-8.0 to +8.0	Offsets have no meaning to 16 MHz bandwidth
Baseband Bandwidth (MHz)	16	

Table 4. VLBI and Wideband VLBI Science Receiver Characteristics (Continued)

Parameter	Value	Remarks
Baseband Resolution (MHz)	1	
Number of Subchannels Available for each VSR/WVSR	16	Each of 4 channels has 2 narrowband and 2 wideband subchannels
Subchannel Tuning		
Tuning (MHz)	±8	From center of baseband
Resolution (Hz)	<1	
Recording Bandwidths		
Narrowband (NB), kHz	1 – 100	1 – 4-subchannels
Wideband (WB), MHz	1 – 16	1 – 4-subchannels
Resolutions (bits/sample)	16 – 1	Depends on selected bandwidth. See Table 2 for available resolutions
Time Tagging		
Resolution (s)	1	Data is time tagged once per second
Accuracy (μs)	1	With respect to station clock
Signal Detection Display		1 for each subchannel being recorded
Number of points in FFT	100 – 4096	Default is 100
Spectra Averaging	1 – 100	Default is 10
FFT Interval (s)	1 – 10,000	Default is 10

2.7.1 Frequency Stability

Frequency stability of the ground station is characterized by means of Allan deviation. RS System Performance Testing (SPT) has been conducted with the exciter, transmitter, the low noise amplifier (LNA), and the Radio Science open-loop receiving equipment. In this test configuration, an uplink signal generated by the exciter is frequency shifted via the test translator to a downlink frequency. The downlink signal is injected at the front-end of the LNA and passed through the RF-IF downconverter, which provides the IF signal to the RSR. SPT excludes instability in the frequency and timing equipment and the mechanical vibrations of the antenna. This is because frequency and timing instability is cancelled out, while the mechanical vibrations of the antenna are not included in the test configuration. Measurements of these items can be obtained via other means, making it possible to provide an estimate of the overall frequency stability for the stations.

Repeated SPT measurements have provided the basis of estimating the Allan deviation over a specified integration time for the ground station. Table 4 shows the 2-way Allan deviation numbers that any DSN ground station can achieve. These estimates include all elements in the ground station that constitutes the measurement path through which the RS data are obtained. The values shown are meant to be the upper bound for performance (i.e., the not-to-exceed numbers). The measurements and analysis have accounted for the various station types (HEF, BWG, 70m), the different frequency band combinations (S, X, and Ka), and various system configurations.

Currently there are no data for the downlink-only measurements so that uplink and downlink performance can be separated. However, there is plan to conduct such measurements for the various frequency bands and configurations in the future to enable the separation.

2.7.2 Phase Noise

Phase stability (Spectral Purity) testing characterizes stability over very short integration times. The region of the frequency band where phase noise measurements are performed can be as far as 10 kHz off the carrier frequency. Such measurements are reported in dB relative to the carrier (dBc), in a 1 Hz band at a specified distance from the carrier.

Phase noise data have also been captured as part of the SPT measurements. Table 5 shows the not-to-exceed phase noise levels for the different frequency bands, at specified offsets. As is the case with frequency stability testing, these numbers have been obtained through many repeated SPT measurements. They represent what the DSN can achieve under normal operation conditions.

2.7.3 Amplitude Stability

Amplitude stability tests measure the amplitude fluctuations produced by the open-loop receiving system relative to a constant (mean) amplitude input signal. The amplitude stability performance is specified in terms of a threshold on the amplitude fluctuations relative to the mean amplitude, and the corresponding probability that such fluctuations will not exceed such a threshold. Analyses with the collected data indicate that the 1-sigma number (67% of the time) of the amplitude stability at a given DSN station over a 30-minute observation at any frequency bands is less than 0.2 dB. This number includes the gain variation due to antenna pointing errors.

2.8 Precision Telemetry Simulator

The Precision Telemetry Simulator (PTS) is an external device that provides IF test signals for performance verification of the radio science equipment. Its signals are generated in the digital domain and subsequently converted to analog, with signal conditions driven from predicts. At least two simulated signals can be generated, each having its own characteristics in terms of Doppler and signal level, etc. The PTS signals are injected into the RS receiver via the FSP IF Switch.

Table 5. Two-Way (Uplink and Downlink) Allan Deviation Estimates

Averaging Time, s	**Allan Deviation**			
	1	**10**	**100**	**1000**
Station				
34-m HEF / 34-m BWG / 70-m	7.0×10^{-13}	2.0×10^{-13}	3.0×10^{-14}	5.0×10^{-15}

Table 6. Uplink and Downlink Phase Noise Estimates

Offset from Carrier, Hz	**Phase Noise, dBc**			
	1	**10**	**100**	**10 k**
Frequency Band				
S-band (Uplink or Downlink)	–63	–69	–70	–70
X-band (Uplink or Downlink)	–63	–69	–70	–70
Ka-band (Uplink or Downlink)	–50	–55	–57	–57