Spectral Analysis Tool (SAT) for Radio-Frequency Interference Analysis and Spectrum Management

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A microcomputer-based software for analyzing radio-frequency interference is presented in this article. The latest enhancement (Version 5) of the Spectral Analysis Tool (SAT) contains numerous features essential for effective spectrum management. Included in the SAT windows menu are editors of signal/interference, filters, spikes, power spectrum plots, calculators for spectral power, telecommunication-link budget tables, and interference analysis tables. The configuration menu for the analysis table contains options on antennas, amplifiers, and receivers for ground terminal characterization. The complete software package of SAT, with a Windows installation program, fits within a single 3.5-inch diskette for easy distribution. Signal and ground terminal models are described. Finally, examples of the application of SAT also are included in this article.

I. Introduction

This article introduces the latest enhancement (Version 5) of a spectral analysis software developed at the Jet Propulsion Laboratory. The Spectral Analysis Tool (SAT) is packed with utilities for accurate assessment of the effects of radio-frequency interference (RFI) on a satellite communications system. It has an editor for narrowband- to wideband-modulated signal/interference sources. Additionally, there is a spike editor for inserting continuous sine wave interference to any spectrum created by the signal generator. To simulate the effects of a band-limited channel, SAT has a filter editor to generate any user-defined bandpass filter. These filters can be applied to the power spectrum to achieve various degrees of roll-off, simulating the effects of a band-limited channel as well as front-end spectral shaping and processing. A built-in graphics editor enables viewing and text editing of multiple power-spectra and spectral-density plots with optional modes of low to extremely high resolutions.

Bundled in the tool kits for spectrum management are calculators for signal/interference bandwidth and power, communication-link budget tables, and interference-analysis tables with a choice of antennas, amplifiers, and receivers. The output analysis results are presented in terms of the interference-to-signal-power ratio and of system loss with respect to a baseline system with no interference. Printer utilities

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also are included for either colored or gray-scaled spectrum graphics. For user convenience, support for text printouts on any parameter menus used within SAT also are provided. Currently, the executable platform of SAT is limited to an Intel 80486 processor or higher running on Windows 3.1 and 95/NT-based microcomputers.

In this article, a brief history of SAT development for the Deep Space Network (DSN) and a description of the SAT architecture are presented in Section II. In Section III, the signal and interference models are shown, and the subsystem ground terminal models characterizing the effects of interference on the ground antenna, amplifier, and receivers are covered. Utilities like the link budget table and bandwidth occupancy calculator are covered in Section IV. An example of the application of SAT in spectrum analysis follows in Section V. Finally, an overview of SAT development and a projection of future upgrades are provided in Section VI.

II. SAT Development and Architecture

A. Development

A popular figure of merit for a receiving system under RFI is the interference-to-signal-power ratio (ISR). Numerically, this can be evaluated via integration of the power spectral density of the signal and the interference, which are derived from their respective fast Fourier transforms (FFTs). Due to the limitation of computational speed and memory size, early versions of SAT had only modest capabilities. In response to user demands, the menu for signal/interference was expanded to include generic binary-phase-shift keying (BPSK) with and without subcarriers, quadrature-phase-shift keying (QPSK), offset quadrature-phase-shift keying (OQPSK), minimum shift keying (MSK), multiple-frequency-shift keying (MFSK), frequency modulation (FM)/radar, etc. The effects of pulse imperfection in the modulation process also were included in the Version 3 series. With this added complexity, SAT migrated to the 386-based processor. Other utilities like telecommunication-link budget tables, generic bandpass filters (BPFs), and tone generators then were added. With this increased sophistication, Version 4 was complemented by the increased capability of the matured Windows 3.1 and the new Windows 95/NT operating systems using Pentium-based processors. The latest Version 5 was enhanced further to include generic digital receiver models and system loss as the second figure of merit. Furthermore, all of the previous utilities were refined to include more user-friendly features. The resolution now is up to a million-point FFT for both display and analysis.

B. Architecture

The predecessors to SAT were coded in Fortran, and simulations were run on the VAX. In those days, RFI analyses were done primarily using mainframe computers. It was time-consuming to troubleshoot interference problems and to manage frequency assignments. SAT uses C/C++ and is tailored on the Windows graphics user interface for low-cost personal computing. The current software architecture of SAT is shown in Fig. 1. The main part of the software contains the logic for orderly execution of various functions. Most of the other files were written to add certain features (e.g., pulse asymmetry, filters, etc.) or utilities (e.g., power calculators and link budget tables). The remaining files support file input/output (I/O) as well as memory management. Since the software originally was written in C for a 16-bit Windows 3.1 platform, it requires optimization in both "heap" and "stack" memory allocations for efficient computations. The optimization was carried out under the constraint to support various SAT utilities. Over the years, this software has been gradually tuned to operate at near the full capacity of 16-bit Windows-application software. SAT currently is under migration from 16-bit to 32-bit applications in order to take full advantage of the built-in optimization inherited in the latest C++ compiler and Windows multitasking capability.

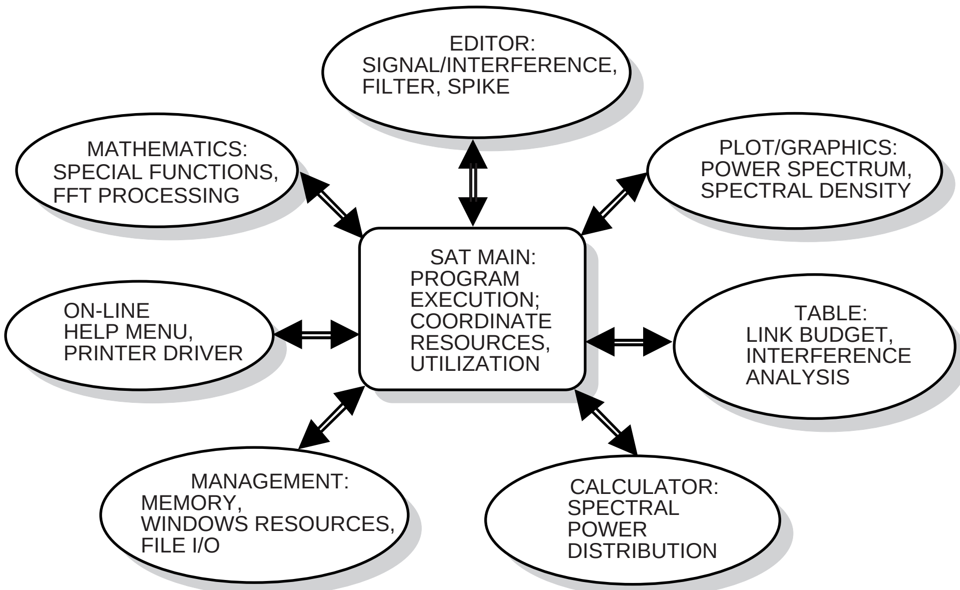

Fig. 1. Architecture of SAT processing elements.

III. SAT RFI Model

A. Signal and Interference Model

The SAT signal/interference library can be divided roughly into two categories. They are the phase-modulated and frequency-modulated signals. When a user first creates a signal, the user can either start with the default parameters or input different parameter values. Upon acceptance of the signal parameters, SAT performs the Fourier transforms and provides temporary storage of the spectra until a save or discard decision is made by the user. These signal-power spectra can be viewed or printed under the display menu. If the spectrum does not meet the expectation of the user, the user can go back to modify the signal again. Spectral plots of some sample signals are shown in Figs. 2 and 3.

As part of the SAT utilities, a user can synthesize a composite real-life signal by appending an arbitrary set of discrete frequency spikes (sine waves) to another signal from the library menu (Fig. 4). Next, the spectrum can be shaped to simulate the effects of a transmitter filter, a receiver filter, and/or a band-limited channel. The filtering operation is achieved by choosing the proper class of filter from a filter library that includes the popular Butterworth, Chebychev, and Gaussian filters. The user then can specify the order and the desired roll-off characteristics. An example of applying various types of filters on a default BPSK spectrum is shown in Fig. 5.

B. Ground Terminal

Most ground stations contain an antenna, a low-noise amplifier, a receiver, and a decoder. Inside DSN tracking complexes, there are different classes of antennas, starting from the smallest size, a 9-meter parabolic dish for Space Transportation System support, to the largest size, a 70-meter beam-waveguide antenna for emergency satellite links. Currently, these antennas can cover frequency bands ranging from 2.3 GHz (S-band) to 32-GHz (Ka-band). The International Radio Consultative Committee (CCIR) antenna-gain model [1] is adopted by SAT for determining the minimum cone angle against interference. The subsystem following the antenna is the amplifier, including field-effect transistor (FET), high-electron-mobility transistor (HEMT), and maser types of low-noise amplifiers. Within the pass-band of the amplifier, SAT compares the interference power to the saturation level of the amplifier. If

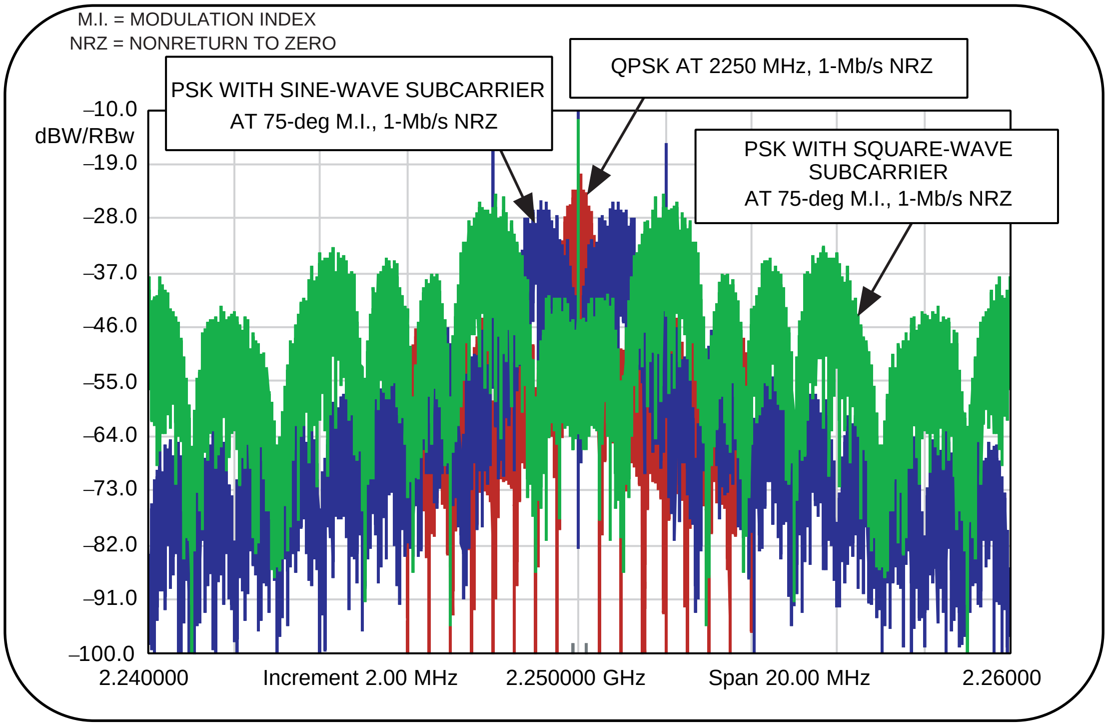

Fig. 2. Sample phase-modulated signals in the SAT menu.

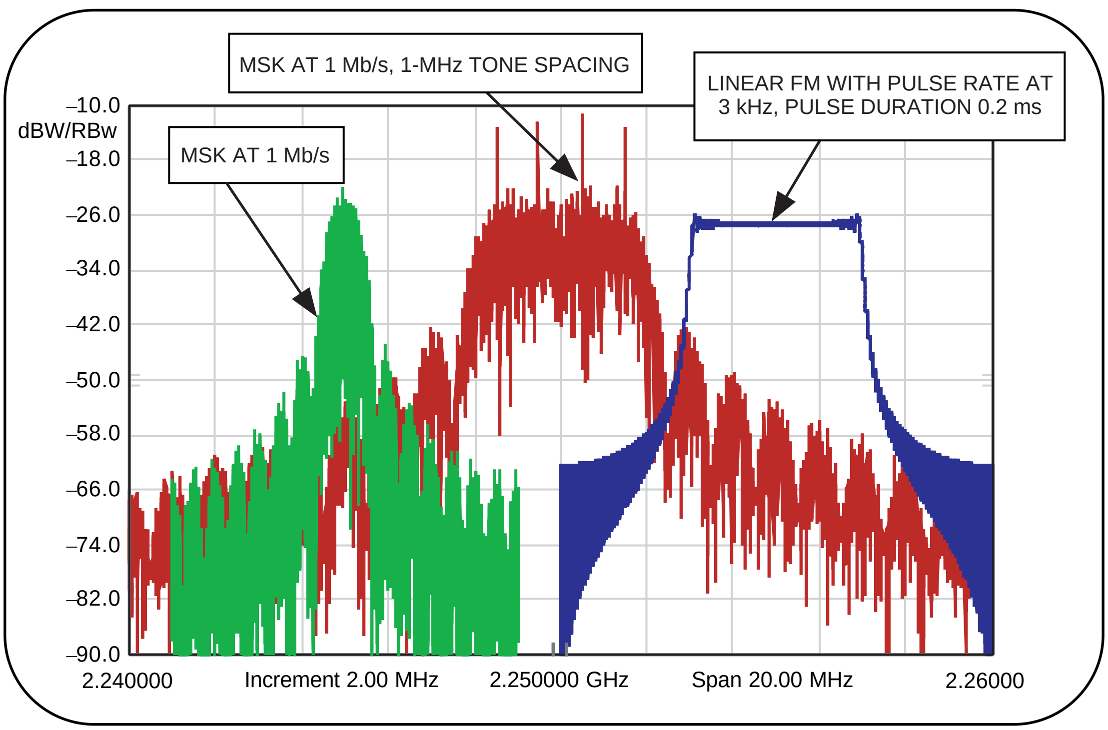

Fig. 3. Sample frequency-modulated signals in the SAT menu.

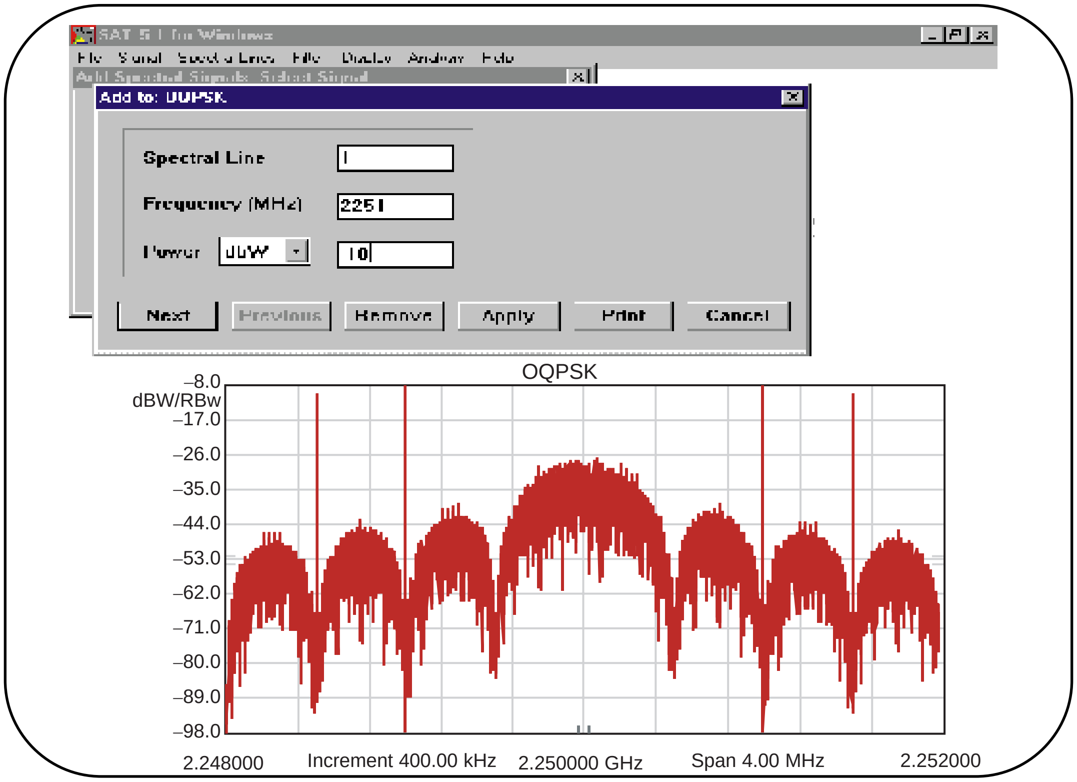

Fig. 4. Application of spikes to a sample spectrum.

the saturation level is exceeded, SAT issues a warning message. Finally, to recover the phase-modulated signal for the deep-space probes, DSN receivers perform coherent phase demodulation via phase-locked loops (PLLs) [2]. An older receiver like the Block III was designed with an analog PLL. The Block IV receiver incorporates a hybrid approach of analog and digital signal processing. The latest Block V receiver uses an all-digital implementation. However, for some of the near-Earth satellites, information is transmitted via frequency modulation. In those cases, the 26-meter subnets equipped with multifunction receivers (MFRs) are designated to process frequency-modulated signals. The sensitivity of the various receivers to interference can be expressed by the receiver system loss, which is described in the following subsection.

C. RFI Receiving System Degradation Model

The RFI degradation model was first constructed by Paul Low from Block III receiver empirical test data of DSN telemetry signals operating under continuous-wave (CW) interference [3,4]. The bit-error-rate (BER) degradation was observed with CW interference operating close to the capture range of the carrier. In developing this model, the CW interference was treated as an extraneous noise, i.e., the increase in bit errors was equated to an increase in system-noise temperature. With this model, the degraded signal-to-noise ratio (SNR) could be computed from the BER of the test data using the complementary error function $\mathrm{Erfc}^{-1}(.)$. For telemetry signals modulated onto a square-wave subcarrier, severe BER degradation was observed when the subcarrier and its odd harmonics were at the proximity of an interference. Assuming the receiver match filter was designed to pass the modulated square-wave subcarrier, an impulse response model then was developed as a function of the frequency offset between the interference and the subcarrier harmonics.

In an attempt to explain the observable of RFI interference on the Block IV receiver, D. Hersey and M. Sue turned to an analytical model of the carrier tracking-loop performance in the RFI environment [5].

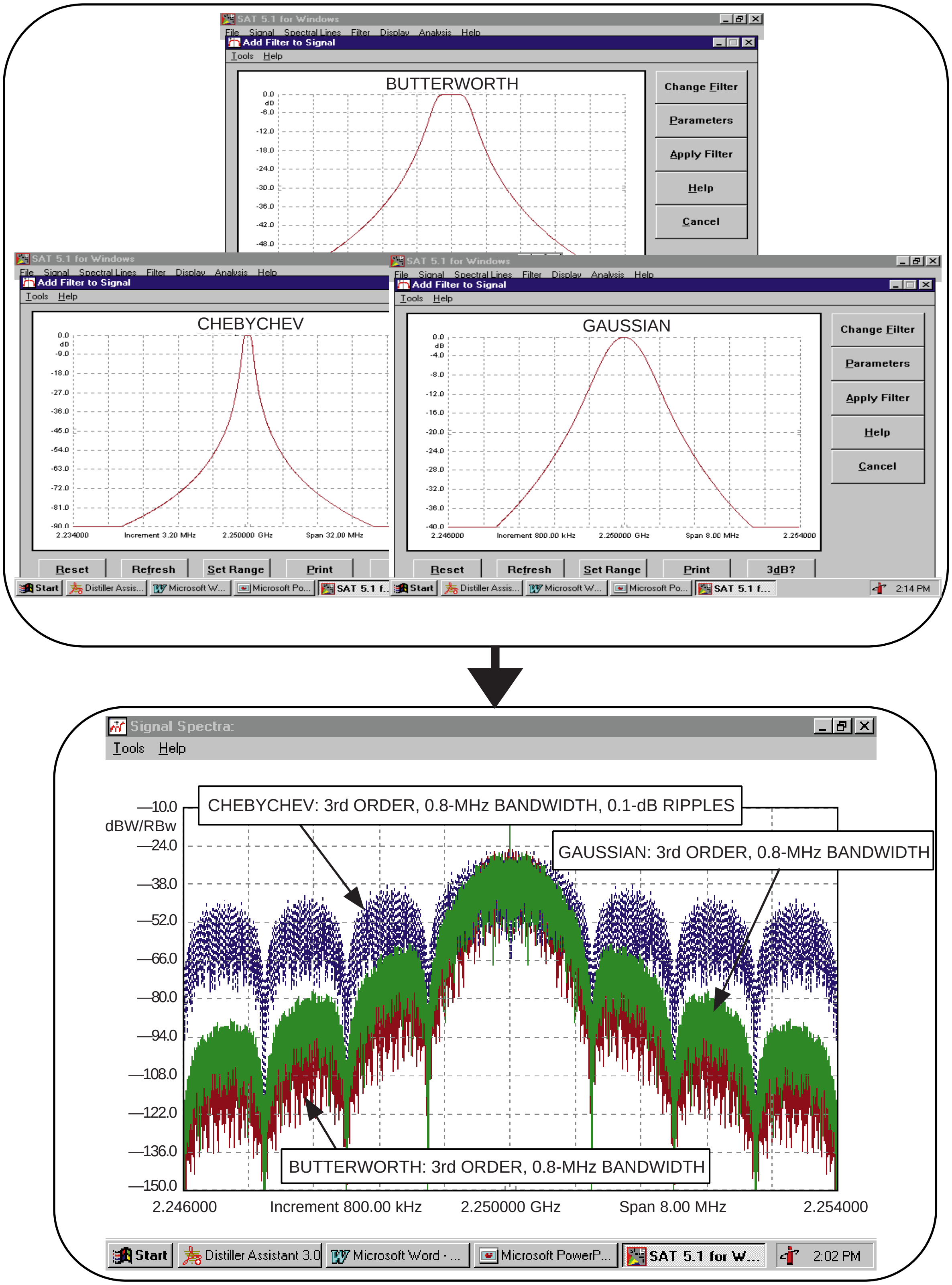

Fig. 5. Filtered S-band spectra of a BPSK signal.

This scenario consisted of a CW tone near the carrier frequency. From linearized PLL control theory, an analytical model was derived. The theoretical prediction was compared to the measurements at Telecommunications Development Laboratory (TDL). Of particular interest is the following parameter set: the drop-lock ISR as a function of the RFI offset frequency and the static phase error, and random phase jitter versus ISR. Results on the carrier-loop degradation were modified for the square-wave subcarrier loop. Next, interference on the symbol loop was evaluated as an SNR degradation due to partial demodulation of the interference. Perfect clock recovery was assumed in the analysis. By extending this result to cover the transition tracking-symbol loop, a complete model on narrowband interference of the Block V receiver was obtained. This model will take into account the relative position of the interference with respect to the data spectrum where the symbol clock is derived. The overall receiver loss can now be decomposed into individual SNR degradations, $L_{\phi c}$, $L_{\phi sc}$, and $L_{\phi sym}$, of the carrier, subcarrier, and symbol loop, respectively, perturbed by interference [6]. These losses are determined by their respective loop dynamics and the relative strength of the signal-to-interference power within the loop bandwidth (Fig. 6). Based on the above characterization, a generic digital receiver interference menu for phase-modulated signals is constructed in SAT for interference analysis (Fig. 6). The spacecraft signal and interference signal characteristics are entered in a different menu.

IV. Communication-Link Budget Table and Other Supporting Utilities

A simple link budget table (Fig. 7) is incorporated in the SAT signal menu. This feature enables the signal power entry to be fed by the estimated signal power based on the link budget calculation. It also can be used as a stand-alone utility for designing a communication link to meet a prescribed bit-error-rate criterion. In order to run the link budget table, the user has to input the amount of gain or loss for each subsystem entry in the table. Another useful utility is the bandwidth occupancy calculator (Fig. 8). It will calculate the bandwidth for rejecting the radiated power of a particular signal. The complementary function is the power calculator that will evaluate the signal/interference power within any specified bandwidth. These utilities are very useful in assisting a spectrum manager to perform the task of frequency assignment.

V. Application of SAT in Spectrum Management

In SAT, the effects of interference are expressed by two performance figures of merit: interference-to-signal-power ratio (ISR) and system loss. Due to Doppler effects on the received signal, there is an uncertainty range on the position of the signal spectrum. To find the worst-case ISR within the uncertainty range, SAT performs successive integrations shifted by the resolution frequency bin until the whole Doppler range is covered. A pairwise comparison yields the worst-case ISR. ISR is a popular figure of merit for interference analysis. The computation involves calculation of the maximum power of the interfering signal in the user-specified analysis bandwidth. However, ISR alone does not discriminate the relative position of the interference to the signal-power distribution of the carrier, subcarrier, and symbol loops as well as their associated harmonics. These effects are covered by another figure of merit called the receiving system loss, which is an equivalent loss in the signal-energy-to-noise-power-spectral-density ratio (E_b/N_o) due to tone interference. System loss is different for various types of receivers under the same interference conditions. A generic digital receiver model is installed in Version 5 of SAT for the evaluation of system loss. An illustration of SAT interference analysis is provided in Fig. 9. In this example, we have a Pioneer downlink signal beyond Saturn's range being interfered with by emission from Cosmos, a Russian low Earth-orbiting (LEO) navigation satellite at an altitude of about 1000 km. Another mission potentially affected by Cosmos is Hubble, with its emergency link operating at 2287.5 MHz. By entering the appropriate mission parameters into the SAT link budget table, the synthesized received-signal-power spectrum automatically will account for the space propagation loss as well as the antenna gains. After bandpass filtering, the power spectra are displayed as in Fig. 9. To perform interference analysis, the ground antenna, amplifier, and receiver have to be properly configured. In this example, a 34-meter antenna is used for Pioneer while a 70-meter antenna is used for the Hubble emergency link. Default

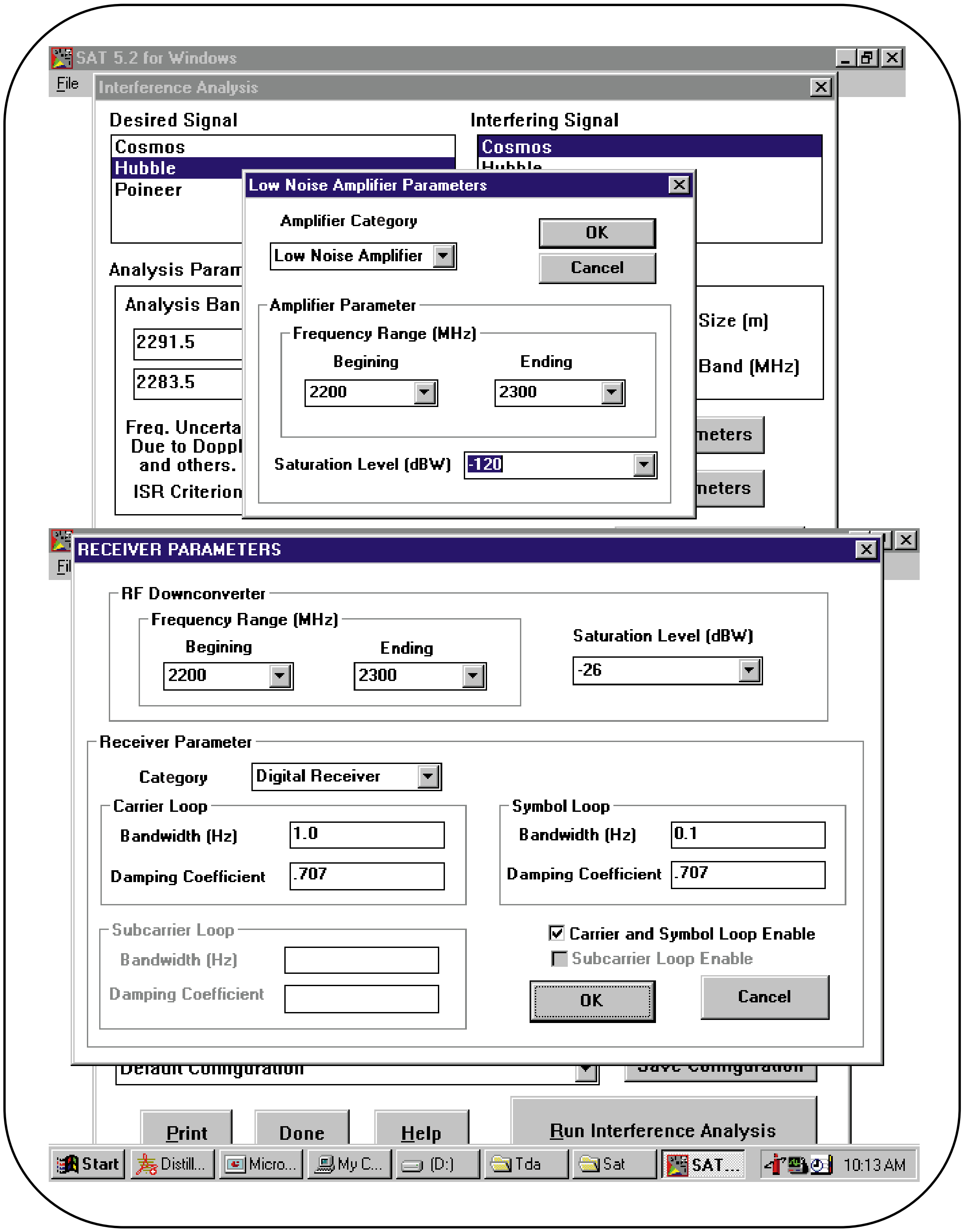

Fig. 6. Amplifier and receiver configuration menu.

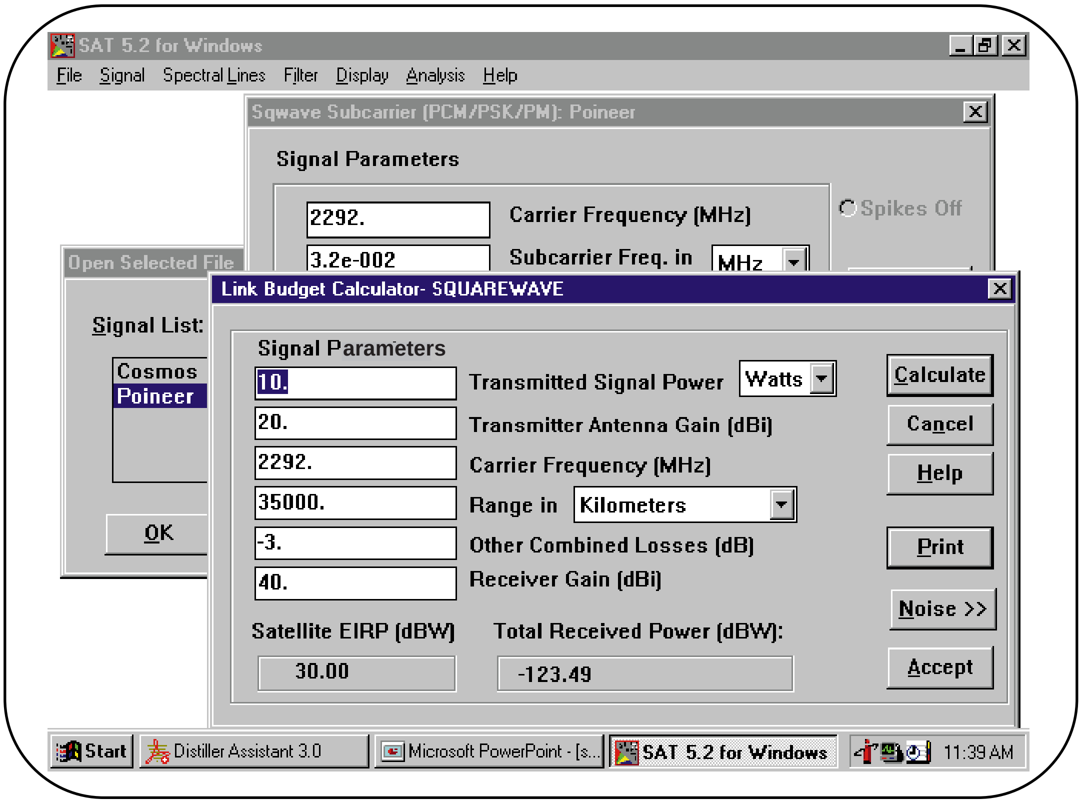

Fig. 7. Telecommunication-link budget table.

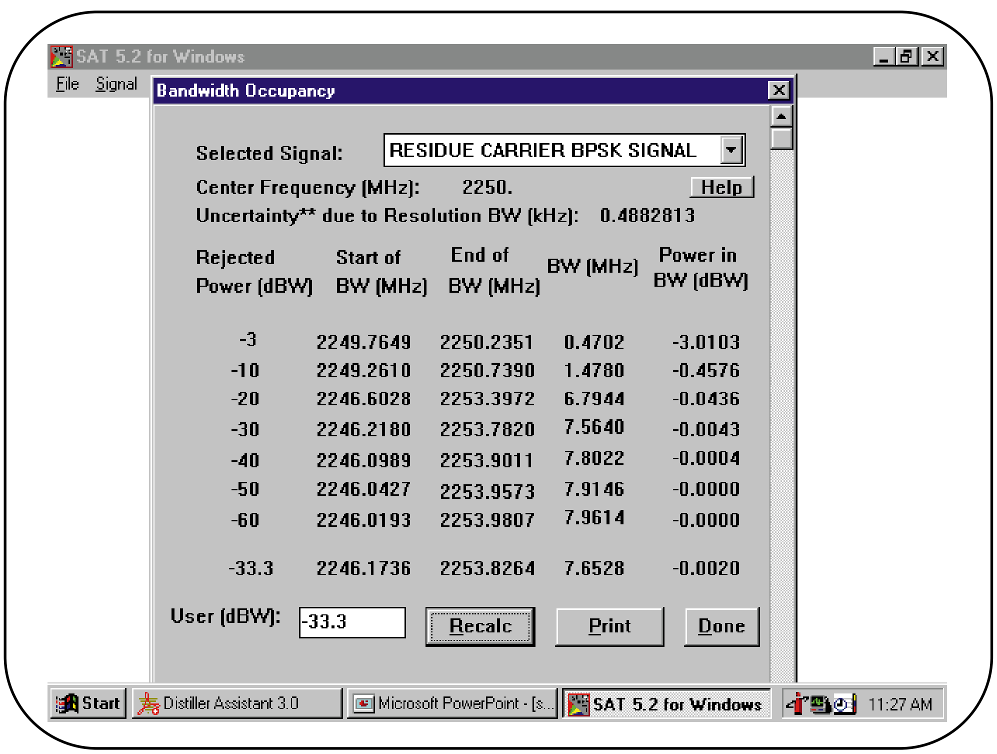

Fig. 8. Bandwidth occupancy power calculator.

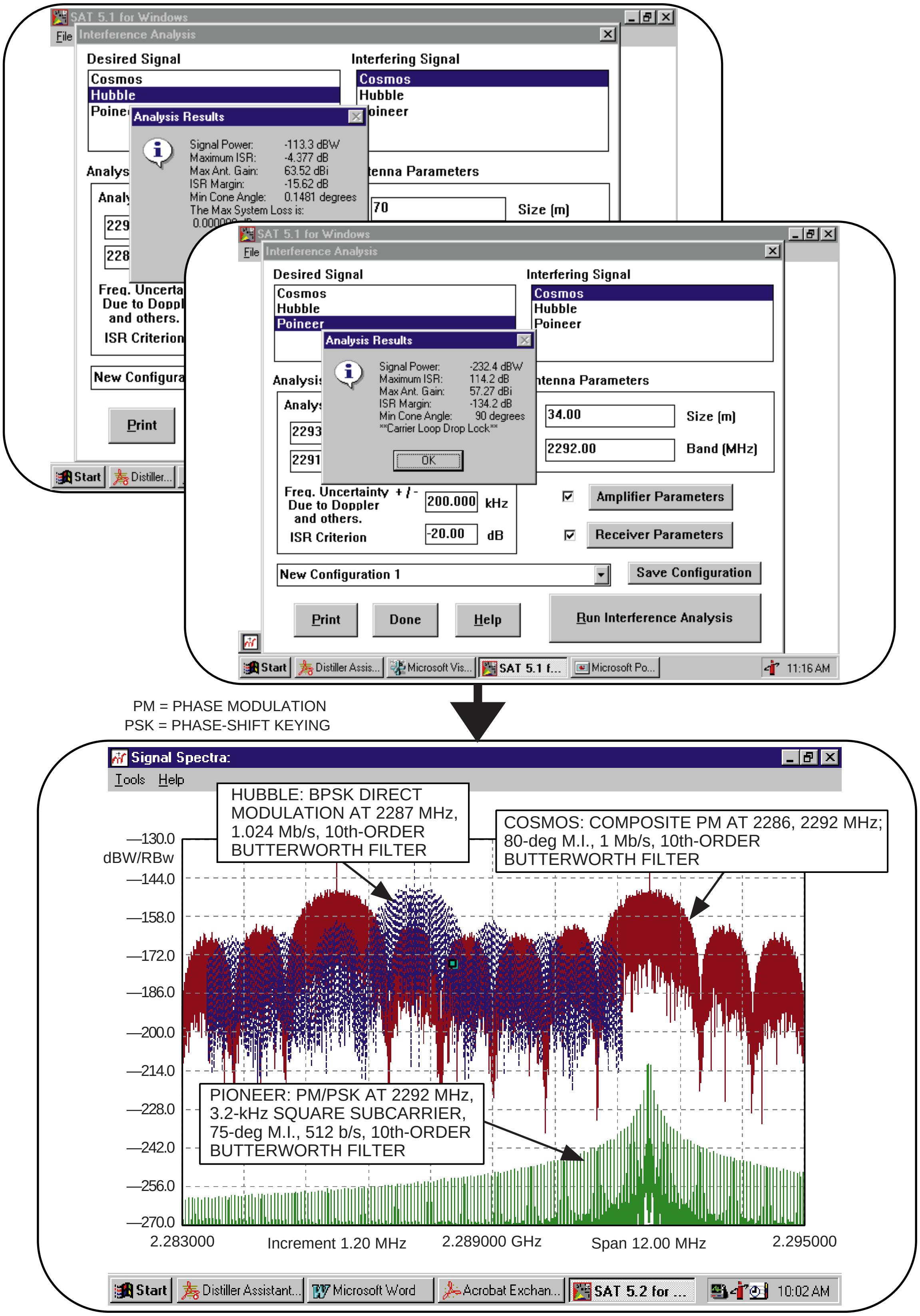

Fig. 9. SAT configuration menu for interference analysis.

settings for the low-noise amplifier (LNA) and the digital receiver are used for this analysis. The results from the "Analysis Results" window show that, with a Doppler uncertainty of 200 kHz, neither mission will be able to meet the −20-dB ISR criterion. The carrier loop will drop lock on the Pioneer downlink. However, Hubble will be able to operate if the angle between the signal from Cosmos and the ground-antenna main lobe is more than the minimum cone angle of 0.148 degrees.

VI. Overview of SAT Development

SAT has been helpful to spectrum managers for conducting desktop interference analyses with a user-friendly interface. In the future, SAT will provide a signal work space where a user can create an arbitrary composite signal/interference. With this capability, SAT can become a versatile design tool for both the communication analysts as well as the spectrum managers. There also are plans to build up the file I/O capabilities so that SAT can share data through an application interface, perhaps with an orbit analysis software or a spreadsheet presentation software.

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