Mars Global Surveyor Ka-Band Link Experiment (MGS/KaBLE)

S. Butman, D. Morabito, A. Mittskus, J. Border, J. Berner,
C. Whetsel, M. Gatti, C. Foster, V. Vilnrotter, H. Cooper,
A. Del Castillo, A. Kwok, J. Weese, M. Speranza
Jet Propulsion laboratory
California Institute of Technology
Pasadena, California

R. Davis, W. Adams, A. McMechen
Lockheed-Martin Astronautics CO.
Denver, Colorado

C. Goodson, G. Bury, D. Reece
Allied Signal Technical Services Corp.
Pasadena, CA

Abstract

NASA's Mars Global Surveyor (MGS), launched on November 7, 1996, includes an experiment! 1 W downlink at Ka-Band (32 GHz) along with the primary 25 W downlink at X-band (8.4 GHz). The signals are simultaneously transmitted from the 1.5 m diameter antenna on the spacecraft and received by the 34 m R&D antenna at NASA's Deep Space Network Complex in California. This allows the performance of both links to be compared under nearly identical conditions.

JPL has been tracking both links since the first Ka-band detection on December 6, 1996. Measurements confirm that operations at Ka-Band would increase data capacity by at least a factor of three compared to X-band.

This article describes the experiment, summarizes results from the cruise phase of the mission and discusses plans for the upcoming aerobraking and mapping phases.

Stan Butman
Jet Propulsion laboratory M/S: 264-214
4800 Oak Grove Drive
Pasadena, CA 91109-8099
TEL: +1 8183547948
FAX: +1 8183935247
email: stanley.butman@jpl.nasa.gov

Mars Surveyor Operation

DATE 5/23/97
PAGES FOLLOWING THIS SHEET 1

FAX COVER SHEET

TO FRANCO BERTOLDI,
IIC INSTITUTO INTERNAZIONALE DELLE COMMUNICAZIONI
VIA PERTINACE - VILLA PIAGGIO
16125 GENOVA, ITALY

FAX # 39 10 2722183

PHONE 39 10 2722383

FROM STAN BUTMAN

MAIL STOP 264-214

FAX # (818) 393-5247

PHONE # (818) 354 7948

MESSAGE:

1. ENCLOSED IS NEW ABSTRACT MERGING D. MORABITO'S AND MY PAPERS TO THE CONFERENCE.

2. THANK YOU. IF YOU COULD IT WOULD HELP SPEED MAIL DELIVERY TO ME IF YOU USE MY MAIL STOP (ROOM #) ON THE ADDRESS LABEL; i.e. WRITE TO STAN BUTMAN MS 264-214

JET PROPULSION LABORATORY
4800 Oak Grove Drive
Pasadena, CA 91 1 09

Mars Surveyor Operation

DATE 5/23/97

PAGES FOLLOWING THIS SHEET 2

FAX COVER SHEET

TO FRANK GARGIONE

FAX # 609-490-2441

FROM Stan Bulman **MAIL STOP** 264 214

FAX # (818) 393-5247 **PHONE # (818)** 354 7948

MESSAGE:

FYI: COPY OF FAX TO BERTOLDI.

Stan Bulman

JET PROPULSION LABORATORY
4800 Oak Grove Drive
Pasadena, CA 911 09

*** CLEAR LOG ***

ADD DOC | ADD CLR | EDIT DOC | LOCATE | PRINT | PRINT LOG

ID Number: 20373

Author's Name: Morabito First Ini: D Middle Ini: D

Srn-code: @ Section: 331 Release: foreign Publication Type: MP

Title: The Mars Global Surveyor Ka-Band Link Experiment
Experimental Results

Abs/Bk/Pap: abs Stamp Date: 03/21/97 Clearance Number: CL 97-0355

Clearance Date: 03/28/97 Credit: Charge Number: 462-42217-0-3310

Transfer Copyright (Y/N): Transfer Date:

Reviewer: Linda Worrel

Comments: Clearance is for the abstract only. Any expansion
of this abstract needs to be cleared before
presenting or publishing.

Exit If Not In Use Press Esc to Abort

THE MARS GLOBAL SURVEYOR Ka-BAND LINK EXPERIMENT (MGS/KABLE-II)

S. Butman, D. Morabito, A. Mittskus, J. Border, J. Berner, C. Whetsel, M. Gatti, C. Foster, V. Vilnrotter, H. Cooper, A. Del Castillo, A. Kwok, J. Weese, M. Speranza
Jet Propulsion Laboratory, California Institute of Technology
S. Butman, M/S 264-214, 4800 Oak Grove Drive, Pasadena, California, 9 I I 09, USA
Phone: 818-354-7948; Fax: 818-393-4257; E-mail: stanley.butman@jpl.nasa.gov

R. Davis, W. Adams, A. McMechen
Lockheed-Martin Astronautics Co.
Denver, Colorado

C. **Goodson, G. Bury, D. Recce**
Allied Signal Technical Services Corp.
Pasadena, California

Abstract

Mars Global Surveyor (MGS), launched on November 7, 1996, carries an experimental 1 W space-to-ground telecommunications link at Ka-Band (32 GHz) along with the primary 25 W downlink at X-band (8.4 GHz). The signals are simultaneously transmitted from the 1.5 m diameter antenna on MGS and received by the 34 m beam waveguide R&D antenna at NASA's Deep Space Network (DSN) Complex in California. This allows the performance of both links to be compared under nearly identical conditions. The Jet Propulsion Laboratory (JPL), operated by the California Institute of Technology for the U.S Nat ional Air and Space Admi nitration (NASA), has been tracking the two signals since December 6, 1996. Measurements confirm that Ka-Band could increase data capacity by at least a factor of three (5 dB) compared to X-band. This article describes the experiment, gives results from the cruise phase of the mission and discusses plans for the aerobraking and mapping phases.

1. INTRODUCTION

The capability to communicate across interplanetary distances has grown by many orders of magnitude since the advent of space exploration 40 years ago. About 19 dB (a factor of 76) carries from antenna gain which scales as the square of frequency. Since 1959 there has been a 8.8 fold increase in the radio frequency; from L-band (0.96 GHz) to X-band (8.4 GHz) in 1977, the primary downlink frequency today (Corlis, 1976). A shift to Ka-Band (32 GHz) is projected to add another 6 dB. The increase in antenna gain with Ka-band is actually 11.6 dB relative to X-band, however, atmospheric noise and attenuation diminishes that by 4 to 5 dB. A further loss of 1.5 to 2 dB is due to DSN antenna imperfections that are insignificant at X-band. In terms of spacecraft mass and power savings, the anticipated 6 dB improvement requires Ka-band transmitters that are no more massive nor less efficient than those at X-band.

To determine if Ka-band will be viable operationally requires performance data to be gathered under varying operating conditions; with weather, DSN antenna elevation and spacecraft modes over a statistically significant period, This is accomplished by MGS/KaBLE which broadcasts in both frequency bands as in Figure 1.

MGS/KaBLE has been functioning well. Data is being accumulated from several tracks per week. An end-to-end telemetry demonstration with ranging was successfully conducted. MGS is pointing within 0.10 deg. and the DSS 13 antenna tracking error is less than 1 mdeg. This paper describes the spacecraft and ground systems and presents preliminary results.

Plans are to continue tracking throughout the MGS mission, particularly to observe propagation effects through the space plasma during Solar Conjunction. MGS/KaBLE will also serve to check out DSS 25, the new 34 m station being readied to support the X-band and Ka-band downlinks on Cassini and DS- I missions.

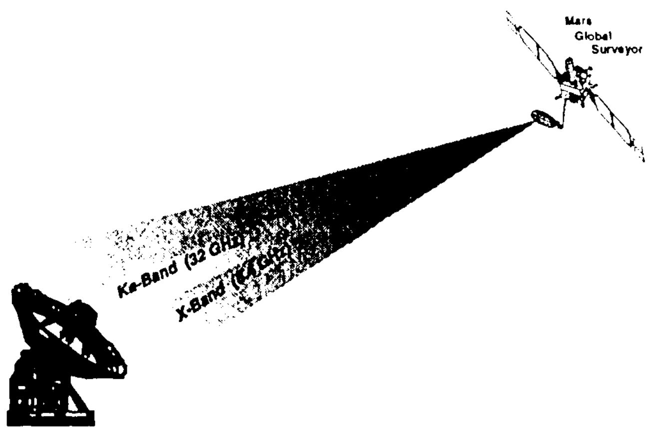

Figure 1. MGS/KaBLE Overview

2. SPACECRAFT CONFIGURATION

The MGS mission was conceived as a low-cost, rapid replacement for the Mars Observer (MO) that was lost on August 18, 1993. MO carried the original KaBLE, which functioned well within its limits, (Rebold et al, 1994). However, with an effective isotropic radiated power (EIRP) of 50 dBm the Ka-band signal on MO was too weak at Mars distance, and at 33.68 GHz it was outside the 31 .8-32.3 GHz band allocated for deep space

The MGS spacecraft contract awarded to Lockheed Martin Astronautics Co. (LMA) in June of 1994 included a functional equivalent of MO/KaBLE. However, the need now was to: 1) maximize EIRP, 2) transmit in the DSN frequency band, and 3) be coherent with the X-band downlink. The challenge was to develop and deliver the enhanced KaBLE-II in 15 months, from October 1994 to January 1996. Thereafter, the spacecraft would not be accessible to non mission critical changes

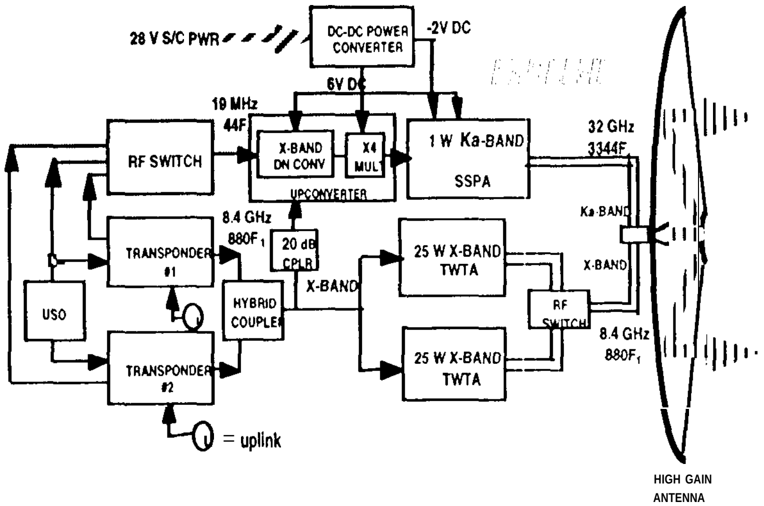

Figure 2. MGS/KaBLE Block Diagram

The design evolved by LMA and JPL is as shown in Figure 2. A low power sample of the X-band downlink from the transponder is upconverted to 32 GHz, amplified to 1 W, and radiated from the dual X/Ka HGA. The 1 W SSPA adapted from another LMA program has an efficiency of 10%. The spare MO HGA X-band feed is replaced by the dual frequency X/Ka-band horn, developed by LMA (Milligan, 1995). Figure 3 shows the MGS antenna. Figure 4 is the integrated spacecraft prior to environmental test. The X-band signal is amplified by one of two 25 W TWTAs and also fed to the HGA.

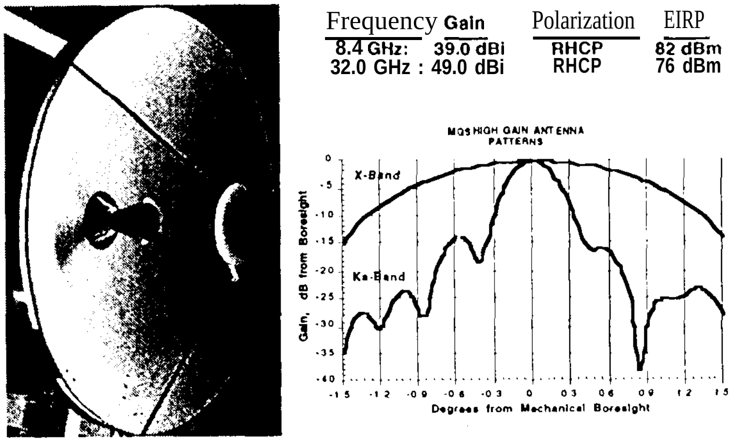

Figure 3 MGS X/Ka-band Antenna

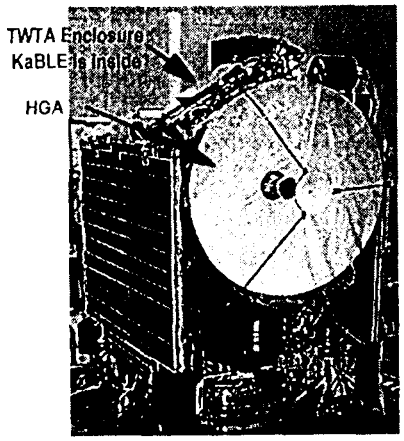

Figure 4. MGS Integrated

The upconverter in Figure 2 first downconverts the 8.42 GHz (880 f1) to 8 GHz (836 f1) then the x4 multiplier produces 32 GHz (3344 f1). That also causes the Ka-band phase modulation to be 4 times the X-band phase modulation. This has certain advantages for KaBLE. The downconverter and x4 multiplier were made for JPL by Milliwave Inc. The DC-DC converter was made by MDI Inc. Excepting the RF switch, all KaBLE components, and X-band power components, arc in the TWTA enclosure mounted on the HGA as in Figure 4. All of KaBLE draws 20 W and has a mass of 1 kg.

The Ka-band dowrriink is coherent with the X-band downiink oniy if the downconverter is driven by the same frequency source as the X-band downiink. The frequency source selection is performed by the RF switch. It can be commanded to select VCO1, VC02 or the USO, or" OFF". This creates several Ka-band frequencies for each X-band frequency. The Ka-band frequency can be either coherent with the X-band downlink or a hybrid combination of the USO and VCO I or VC02 derived frequencies. The possibilities arc given by

$$Fk= 4Fx-0.2Fs \quad (1)$$

where, Fx is the X-band downlink frequency; and Fs is the X-band downlink frequency that would result from the oscillator selected by the switch (nominally the USO is 8.4231 GHz and the VCOS are 8.4177 GHz). A VCO could be locked to the uplink or be free running, which further complicating the Ka-band downlink modes.

3. GROUND SYSTEM CONF1GCJRATION

Figure 5 shows the DSS 13 configuration for KaBLE-II. Functionally it is similar to MO/KaBLE-I. Little new development was required. On the antenna, RF mirrors guide and focus the RF energy onto a feed horn on a low noise amplifier (LNA). The Ka-band monopulse receiver is new, enabling the antenna to autotrack the spacecraft to 1 mdeg accuracy. Conscan, adequate at X-band is not adequate at Ka-band due to atmospheric effects. The DSS 13 antenna efficiency is 43?70-5090 depending elevation and feed position (Morabito, 1996). The system temperature is also elevation dependent and changes with weather.

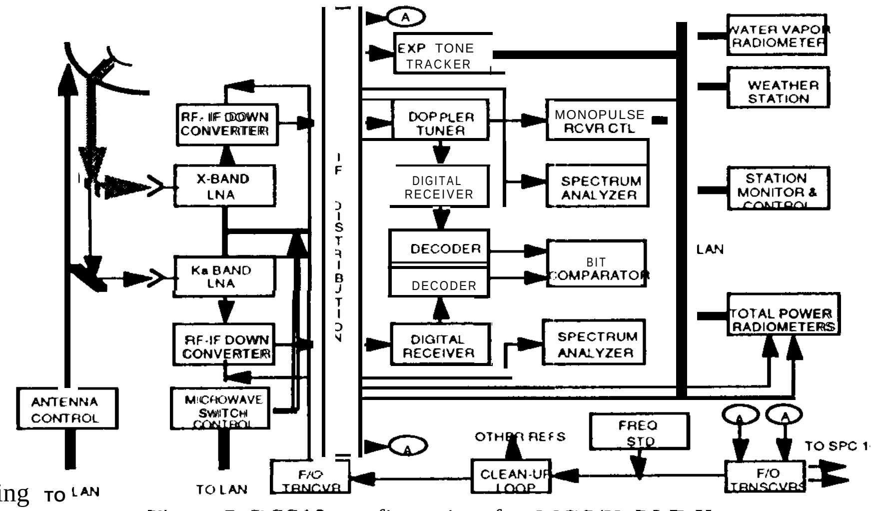

Figure 5. DSS13 configuration for MGS/KaBLE-II

3a) Monopulse Feed-LNA Package

The package generates a low noise sum channel signal and an error channel signal. The signal from the sum channel is downconverted to 300 MHz IF, filtered and distributed for processing by other equipment. The LNA package of feed horn, other microwave components, and HEMT amplifiers is cryogenically cooled. The total DSS 13 system noise temperature with this Monopulse LNA is 83 K at zenith.

When the antenna is pointed directly at the spacecraft, the signals arrive along the axis of the horn and only the TE11 mode is generated. When the antenna is misprinted, signals arrive off axis and TE21 modes are generated. A piece of circular waveguide surrounded by eight directional couplers detect the TE21 mode signals. The direction of pointing error determines the distribution of energy among the eight couplers. The error channel signal is generated by combining the eight coupler outputs in a waveguide combining network.

When the antenna is misprinted, the voltage ratio of the error channel divided by the sum channel is proportional to the pointing error. The direction of the pointing error is proportional to the phase difference between the error and the sum channel signals. Tfre amplitude and phase of the signal in the sum channel and the error channel are extracted from noise by narrow band FFTs and used to calculate pointing error. Spacecraft Doppler is removed in the downconversion process by programming onc of the local oscillators using spacecraft frequency predicts.

During operation, the antenna is initially pointed based on spacecraft pointing predicts. The monopulse computer determines the pointing error based on the FFTs and the. corrects the antenna pointing by sending an elevation and/or cross-elevation offset to the antenna every five seconds. At each update time, the antenna pointing is corrected by 0.4 times the measured pointing error. During most tracks, with a Ka-band signal level of greater than 35 dB/Hz, the monopulse tracking system kept the pointing errors to less than 1 mdeg. During high gusty wind conditions the errors were less than 2 mdeg.

3b) Experimental Tone Tracker (ETT)

The Experimental Tone Tracker (ETT) is a digital phase lock loop receiver which can track up to eight independent sinusoidal signals. It has been very reliable, operating without failure on every KaBLE pass to date. A very useful feature of the ETT is that when locked to a strong signal it can be set to aid a weak coherent signal.

3c) Telemetry Processing Equipment

Two digital receiver-processors, TP-2 and TP-13 (R&D versions of the DSN'S new Block V receivers) arc **used to** receive and demodulate the X and Ka-band downlinks. TP-13 is dedicated to the X-band channel, TP-2 to the Ka-band channel. The receivers acquire and track carrier, subcarrier and symbols. The synchronized and quantized **symbols** arc decoded by surplus DSN Maximum-1 ikelihood Convolutional Decoders (MCDs). The decoded bits arc aligned and compared bit by bit in a bit comparator. The number of disagreements is a measure of Ka-band performance because the MGS X-band link is error free at data rates that Ka-band could support

3d) Total Power Radiometer (TPR)

The Total Power Radiometer (TPR) measures received signal and noise using a 10 to 30 MHz. filters. When the antenna is pointed a fcw degrees away from the spacecraft the TPR measures only the system noise.

4. RESULTS

KaBLE data acquisition and analysis activities started on December 6, 1996 one month after launch and one month ahead of schedule. On that date Earth would bc 33 degrees off the HGA boresight and drifting through the 130-th KA-band sidelobes of the HGA where pointing loss is -53 dB ±5 dB. However, at 8.4 Mkm MGS was detectable when tracked by the ETT in the aided mode. The received signal was 4.8 dB-Hz ±6 dB, as expected.

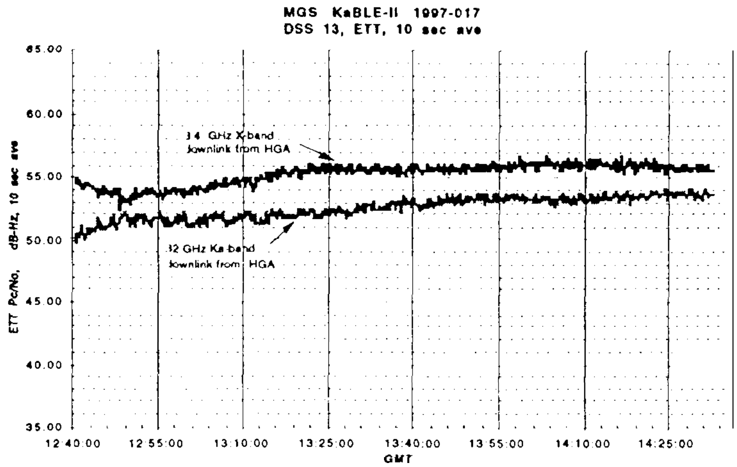

Figure 6. January 171997, first Outer Cruise pass

The next opportunity occurred on January 2, 1997 as Earth drifted through boresight of the HGA. This was strongest Ka-band signal to ever be received from MGS. Modulation was turned off and the distance would never bc shorter. January 17, 1997 was first pass after the HGA was fixed on earth point and radiated X- and Ka-band. Figure 6 is a record from the residual carriers tracked by the ETT.

Figure 7 is a projection of actual Ka vs X-band performance normalized to equal conditions. The difference between the measured Ka-band and X-band data channels (symbol SNR) obtained by the digital receivers(TP-2 & TP-13) was normal ized by adding back preventable deficiencies (fort both X & Ka) from MGS (e.g. 1 watt vs 26 watts), from DSS 13 (e.g. Top) and modulation effects (X-band ranging mod index of 12 deg is 48 degrees at Ka-band). In general, symbol SNR is a good measure of total signal power. The data sidebands have more than 75% of the total signal power and arc thus much less susceptible than the residual carrier to small modulation index variations or other minor effects.

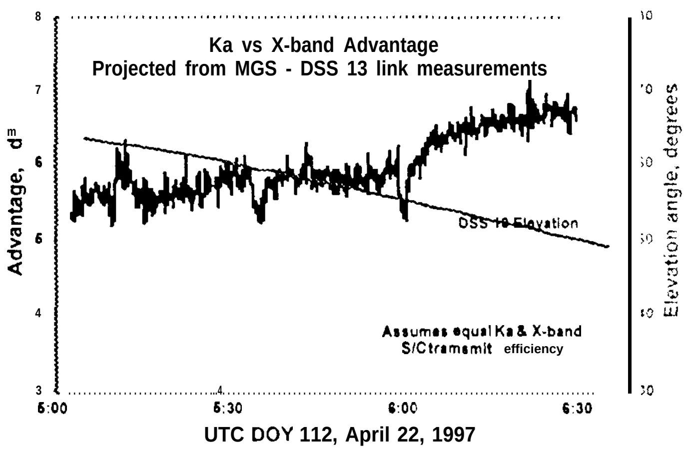

Figure 7. Measure of Ka-band vs X-band advantage

4a) Signal Strengths

A total of 53 3 hour passes were conducted by May 7, 1997. In every case a Ka-band signal was detected, locked onto and tracked for significant duration during each track. The received signal strengths vary due to spacecraft range, pointing, modulation index, ranging modulation, ground station configuration, weather attenuation, uncertainties **in pointing,** KaBLE flight temperature and downlink frequency.

Most data were acquired by tracking the residual carrier with the ETT. Telemetry and ranging modulation suppressed the residual carrier by varying amounts, depending on modulation index.. In order to estimate the total signal power and the EIRP for comparison purposes, the measured carrier was "corrected" for these suppression effects. These "corrected" values of EIRP were generally not in agreement for Ka-band. This can be attributed to various factors with the flight hardware (modulation index uncertainty, spurs at different frequencies and operating temperatures, etc.). However, when telemetry and ranging was off and all of the power was in the carrier, as on April 2, 1997, the observed Ka-band SNR agreed with prediction to within 1 dB. Figure 8 illustrates this during the "quiet" period when DSS13 antenna testing was halted. This pretty much confirms the expected 5 dB Ka-band link advantage over X-band and confirms that antenna pointing loss has been minimized indirectly confirming the predicted 5 dB Ka-band link advantage and by implication negligible spacecraft antenna pointing loss. EIRP was inferred as follows: The received carrier power was estimated from the ETT Pc/No signal/noise and the TPR noise measurements. The received data were then corrected for ground station gain (Ref. 3), atmospheric attenuation, and space loss, producing estimates of EIRP at the spacecraft. These EIRP estimates were then compared with predicted "ideal" EIRP of 82 dBm at X-band and 76 dBm at Ka-band.

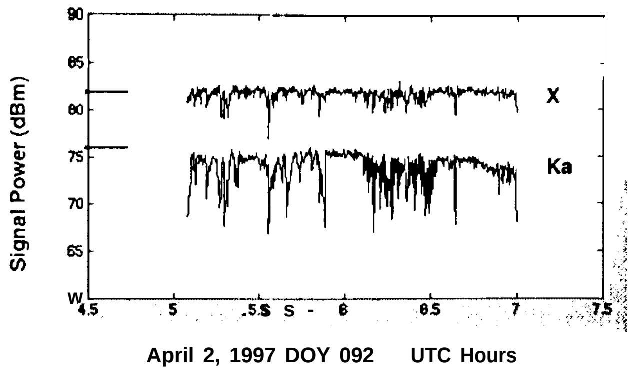

Figure 8. MGS X & Ka-band EIRP inferred from ETT. (fluctuations arc due to concurrent DSS13 antenna test)

During these 53 passes for which Ka-band signals were detected, the estimated atmospheric attenuation ranged from 0.1 to 0.5 dB. Data will continue to be. acquired under a wide variety of weather conditions allowing a statistical data base to be accumulated for the purpose of characterizing weather attenuation and scatter effects.

4b) Frequency Data Analysis Results

X and Ka-band frequency estimates by the ETT were processed to produce residuals using a Radio Science software package (Morabito, 1995) with the trajectory provided by the MGS Navigation Team. Figure 9 shows the residuals of the frequency difference (X - Ka/3.8) from January 2, 1997. Figure 10 plots their Allan deviation.

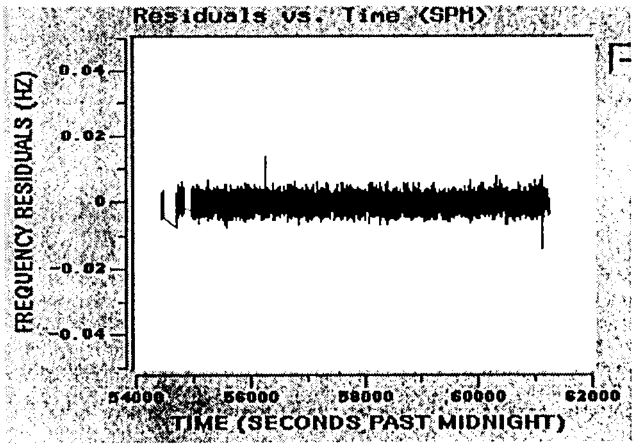

Figure 9. X-Ka-band residuals

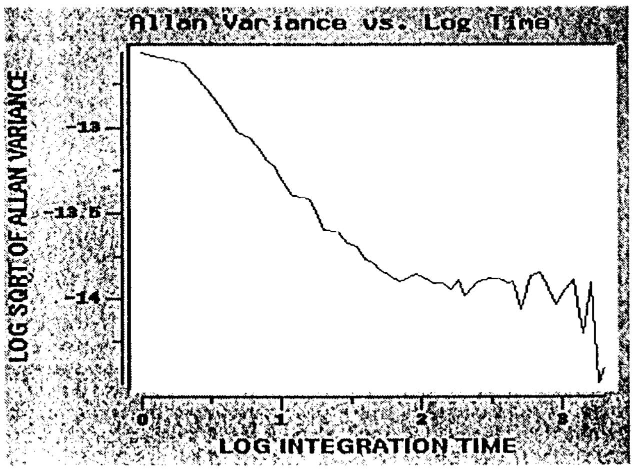

Figure 10. Allen Deviation

The table on the right summarizes the results for tau of 1, 10, 100 and 1000 sec. The X-band and Ka-band Allan deviations are in good agreement The I-see values are in agreement with individual estimates based on thermal noise. Allan deviations were higher than pre-flight values for the USO; probably duc to unmodeled spacecraft motion.

τ (W’)	X-band $\sigma_y(\tau)$	Ka-band $\sigma_y(\tau)$	Pre-flight $\sigma_y(\tau)$
1	3.12	1.86	1.2
10	1.88	1.85	0.64
100	1.45	1.31	0.72
1000	5.98	5.82	0.89

4c) Telemetry Demonstration

An end-to-end Ka-band telemetry demonstration was conducted during April 14-May 2, 1997. The Mars Surveyor Operations Project (MSOP) received and displayed telemetry transmitted at 2 kbps by MGS over its experimental Ka-band link as well as over its operational X-band link. Figure 11 shows the monitor terminal displaying plots of spacecraft engineering data as received on both frequencies. There were no errors as both links were above margin.

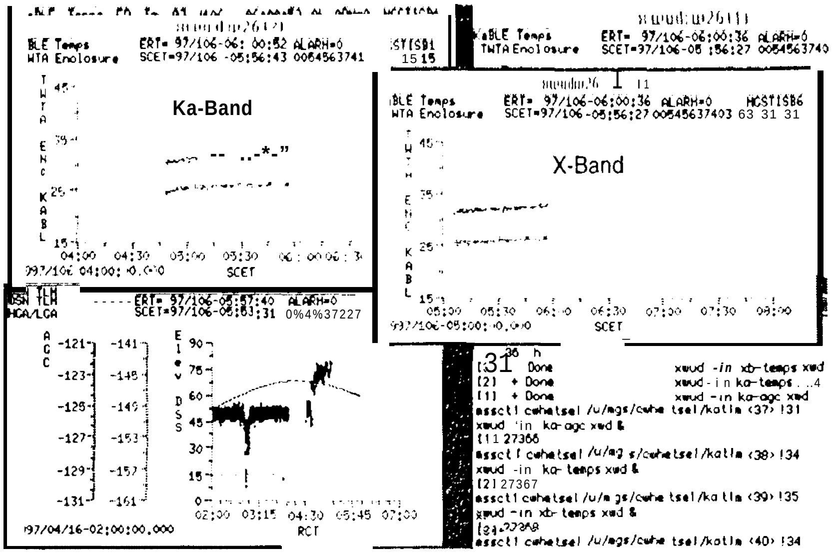

Figure 11. Spacecraft Engineering Telemetry Display

The Ka-band radio signal was received at DSS 13 while DSS 15 provided the operational X-band uplink and downlinks as depicted in Figure 12. Both the X-band downlink from DSS15 and the Ka-band downlink from DSS 13 were downconverted to IF and cabled over to SPC- 10 for telemetry and radio metric processing, and delivery to the project data base. Dual frequency ranging was also obtained at Ka-band and X-band.

4d) Range Data Demonstration

'I'he system configuration for MGS simultaneous Ka- and X-band ranging involved the operational DSN station, DSS- 15, which provided the X-band uplink signal and received the X-band downlink. This is the standard operational two-way ranging configuration with the spacecraft. The R&D station, DSS- 13, which was in the listen-only mode tracked the Ka-band signal, downconverted it to 300-MHz IF, and then sent the signal through optical fiber to the Block-V Receiver (BVR) located in the main Goldstone complex at SPC- 10. The two Receiver Channel Processors (RCP 1 and 2), part of the BVR of DSS- 15, simultaneously demodulated 1> S- 13 Ka-band IF on RCP1 and DSS- 15 X-band IF on RCP 2. Ranging baseband correlation is done in the Sequential Ranging Assembly (SRA). The Metric Data Assembly (MDA) formats radio metric data (including ranging data), which are sent to the Navigation subsystem (NAV) for processing. The data used in the analysis are extracted from a computer server which stores the files forwarded by the NAV. This configuration uses the DSS-13 front-end to track the Ka-band downlink, however, data demodulating, processing, and formatting are all performed by DSN operational equipment.

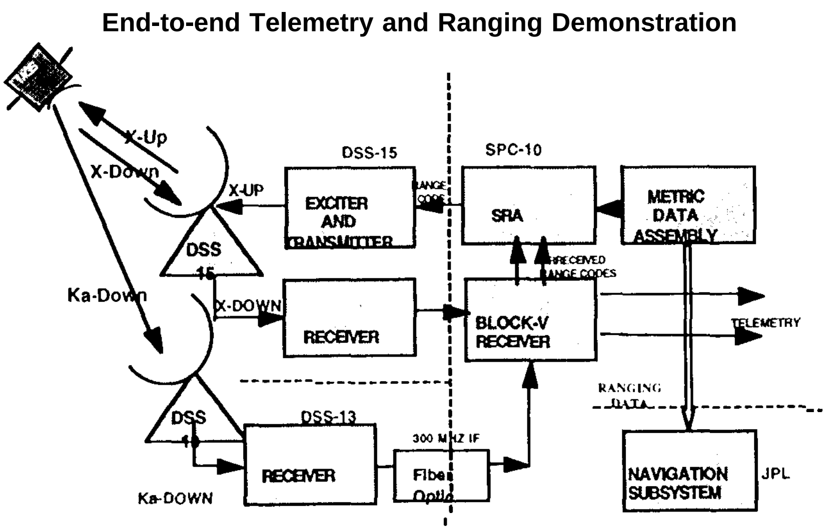

Figure 12. Configuration for end-to-end demonstration

The ranging power-to-noise Pr/No, values as measured by the SRA are comparable as expected. The X-band link has about 12 dB more total power-to-noise (Pt/No) than Ka-band, however the X-band ranging modulation index is only 12.2°, while at Ka-band it is multiplied by 4 to 50°. This makes Pr/Pt 11 dB greater at Ka-band

The following table presents the average measured Pr/No, the standard deviation(sigma) of the residues plots, and the computed sigma's based on the thermal noise model which uses the average measured Pr/No anti the actual integration time T l=20 seconds.

	Average Pr/No (dB-Hz)	Residues Plots Sigma (RU)	Computed Sigma (KU)
DOY 107: Ka-band	33.2	7.4	0.7
X-band	33.8	1.8	0.7
DOY 108: Ka-Band	32.1	9.3	0.8
X-band	33.4	2.0	0.7

The Range Unit (RU) is related to the transmitting (uplink) frequency, Ftx, of DSS- 15 by: (1 RU = 1 / (16 * 11 * Ftx/1200)). Here, 1 RU = .951601871 ns for 97-107 and 0.951601611 ns for 97-108.

Range residuals on each SRA channel are displayed in Figure 13. The residuals shown are what remains after a 6-degree polynomial curve is fit to each data set separately. The residuals at Ka-band are about 4 times as large as at X-band. This may have been caused by a deteriorating circuit card in the SRA, which was discovered and replaced several weeks later following tests with Pathfinder. A re-test with DSS 13 is planned to corroborate.

X/Ka-band simultaneous ranging using DSN operational equipment was successfully demonstrated.

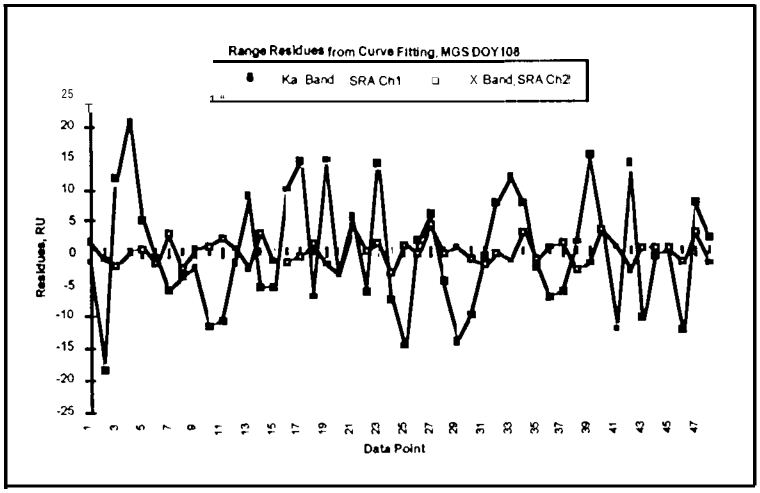

Figure 13. Ranging residuals

5. CONCLUSION

The MGS/KaBLE-II link experiment measured signal strength estimates which were in agreement with predicted values, frequency residuals which were in agreement between bands, range data which demonstrated Ka-band ranging, and delivered telemetry in real time to the MGS project. The demonstrations indicate feasibility not an operationally ready system. There are, as alluded to in several places before, many variables that need to be understood and controlled at both ends of the link before Ka-band operation becomes routine and predictable.

The relative performance of X and Ka-band over an extended period will continue to be quantified as additional data are acquired under a wide range. of elevation angles and atmospheric conditions. Data will also be acquired during periods when MGS is angularly near the sun. During superior conjunction in May 1998, the unmodulated carrier using the Ultra-Stable Oscillator (USO) will be used to gather statistics of the phase variations versus solar elongation angle. Because Ka-band signals pass more easily through the Sun's corona than do X-band signals, Ka-band communications should be more easily maintained during solar conjunction.

ACKNOWLEDGMENTS:

We would like to thank J. Beerer, G. Cunningham, L. Deutch, C. Edwards, R. Horttor, W. Lee, C Mcannaly, G. Pace, W. Rafferty, C. Stelzried, T.Yan, J. Yuen, S. Portas and H. Fosque for their support, guidance and continuing interest in this work; the DSS- 13 station personnel for conducting the experiments (J. Crook, G. Farner, J. Garnica, R. Littlefair, R. Reese, and L. Smith); L. Skjerve and L. Tanida for development and operation of the HP SAS; R. Clauss and T. Rebold for consultation; J. McCluskey and C. Stelzried for scheduling support; and M. Ryne for navigation support. The support of the MSOP sequence and spacecraft operation teams at JPL and LMA is gratefully acknowledged.

This paper presents the results of onc phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

REFERENCES:

I) Corliss, W. R., "History of the Deep Space Network", May 1, 1976, NASA Report No. CR-151915.

2) T. A. Rebold, A. Kwok, G. D. Wood, and S. Butman "The Mars Observer Ka-Band Link Experiment", The Telecommunications and Data Acquisition Progress Report 42-1 I 7, vol. January - March 1994, Jet Propulsion Laboratory, Pasadena, California, May 15, 1994.

3) D. D. Morabito "The Efficiency Characterization of the DSS- 13 34-Meter Beam-Waveguide Antenna at Ka-band (32.0 and 33.7 GHz) and X-band (8.4 GHz)", The Telecommunications and Data Acquisition Progress Report 42-125, vol. January - March 1996, Jet Propulsion Laboratory, Pasadena, California, May 15, 1996.

4) D. D. Morabito and S. W. Asmar "Radio Science Performance Analysis Software", The Telecommunications and Data Acquisition Progress Report 42-120, vol. October - December 1994, Jet Propulsion Laboratory, Pasadena, California, February 15, 1995, pp. 121-152.

5) T. Milligan, "Compact Dual Fand Feed for Mars Global Surveyor", !995 IEEE AP-S International Symposium and USNC/URSI Radio Science Meeting, Newport Beach, California, June 18-23, 1995.