Installation of the Mu2 Ranging System in Australia

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The Mu2 Ranging System has been installed at DSS 42/43 in Australia. It was used to support the 1979 Viking Relativity Experiment and is currently supporting Voyager Navigation and the Advanced Systems Program. This article describes these tasks as well as Mu2 software and hardware modifications prior to installation.

I. Introduction

In October of 1978, the Mu2 Ranging System was installed at DSS 42/43 in Australia. The Mu2 is a research and development tool which has supported all range transponder-bearing spacecraft since Mariner Venus Mercury 1973. It has provided the data required by several Theory of Relativity experiments and investigations into the nature of the solar corona. In the present case the Mu2 corroborated laboratory research by utilizing the Voyager 1 and 2 spacecraft and obtained data for the Viking Project Test of General Relativity. This article reports the rationale leading to the installation in Australia, the results of the effort, the engineering involved, and the intended future use of the Mu2.

Let us review, in a most cursory fashion, some of the features of the Mu2 (Ref. 1). All ranging systems measure the round trip time delay involved in transmitting a signal to some object and receiving a corresponding echo. The Mu2 is a binary sequentially-coded ranging machine. Its signal is a square wave whose period is regularly doubled. The signal is phase modulated onto a carrier, transmitted to a spacecraft which transponds it back to earth. The phase difference between the transmitted and received square waves is a direct measure of time delay (and an indirect measure of range). Detection and correlation of the received signal is accomplished digitally in the Mu2. This distinguishes it from the standard DSN ranging system, the Planetary Ranging Assembly (PRA), which uses analog techniques. Digital radio frequency signal processing allows the Mu2 to be fully automatic and exceptionally stable in performance.

Other distinguishing features include full two channel (usually S- and X-band) operation and square wave range codes up to 8 MHz in frequency. The PRA, on the other hand, is limited to having only a single code available on its second channel and a maximum code frequency of 500 kHz. The advanced software system, within the Mu2, facilitates radio science measurements under adverse signal conditions and also aids research into new ranging techniques.

This article is organized into four sections. First the rationale behind the reinstallation of the Mu2 into the DSN will be presented. Second the significant results of the effort are described. Third, we explain the hardware and software changes implemented in the Mu2. Finally, in the last section, the future of the Mu2 is proposed.

II. The Why

Installation of the Mu2 at DSS 42/43 was motivated by the Viking Radio Science Team, the ongoing advanced radiometric research program and the DSN commitments for Voyager Navigation. We discuss each in turn.

A. Viking Radio Science

During 1976, the Mu2 successfully supported both the solar corona and the Theory of Relativity experiments when Mars went through superior solar conjunction. Facilities available in the Mu2 software and hardware allowed it to reliably obtain range data when the radio ray-path was close to the solar disc. These include:

(1) Full dual channel operation which allows measurement of S-X differential delay to a maximum of 2 seconds. The PRA is limited to 2 μsec differentials.

(2) Full correlation voltages allow real-time assessment of range validity even when Doppler is unreliable – as during solar conjunction.

(3) Extensive clean-up of noisy Doppler signals by a quadrature filtering technique enables the Mu2 to range during periods of great carrier phase jitter.

(4) Any of the range codes (8 MHz to 0.5 Hz) available on the Mu2 can be used as the initial or highest frequency code. Thus the precision of the range measurement can be matched to the modulation phase jitter in the range channel. Time is not wasted on integrating components whose period is a small multiple of the phase jitter thereby increasing data yield.

(5) Fully automatic operation removes error sources due to incorrect phasing of the range code demodulator 10 MHz station reference and inconsistent manual adjustment of analog front-end attenuators.

(6) The Mu2 uses "Tutorial Input" (Ref. 2) as an operator interface. This highly interactive system enables real-time modification to parameters in response to changing signal conditions.

Due to these capabilities, the Mu2 has ranged demonstrably closer to the Sun than the PRA. The results of the 1976 solar conjunction include a four-fold improvement in the confirmation of Einstein's Theory of General Relativity (Ref. 6). Reinstallation of the Mu2 into the DSN was requested by the Viking Radio Science Team for coverage of the January 1979 Mars superior solar conjunction.

B. Advanced Radiometric Research

An article by Layland, Zygielbaum and Hubbard (Ref. 3) described experiments which used frequency band-limiters to remove distortion from the received or "downlink" ranging signal. Recall that the Mu type ranging systems (Mu1, Mu2 and PRA) suffer from wave form distortion of the range code due to asymmetric amplitude and phase distortion of harmonics of the range code square wave. This problem is compounded by a mismatch between the actual correlation function pro-

duced by the ranging hardware and that assumed by the software. In essence, the software assumes that the returned signal is a square wave while limitations of the DSN transmitter, spacecraft transponder, and, to a lesser extent, the DSN receiver, reduce the signal to a badly distorted sine wave.

When using the normal 500-kHz high-frequency code, about 18.5 ns of peak- to-peak range error appear during ranging pre- and post-track calibrations through the test translator. Measurements when using the proof test MVM '73 transponder showed distortions of 7.4 ns. The transponder has less error because it is band-limiting at ±1.5 MHz, thereby removing the adverse effects of distorted fifth and higher-order harmonics. Unfortunately the third harmonic is still propagated and in fact is further corrupted by the transponder.

Ranging accuracy can be enhanced by simplifying the spectrum of the range code. One way to accomplish this is to utilize a 1-MHz initial code. The 1-MHz square wave is corrupted in transmission to the spacecraft. Fortuitously, however, the band-limited transponder will filter out the 3-MHz third harmonic as well as all higher harmonics prior to any nonlinear transponder elements. To remove any harmonics generated by the spacecraft transmitter or within the DSN receiver, a band-pass filter is installed in the receiver IF line connected to the Mu2. In this manner the Mu2 is presented with a well-scrubbed sine wave corresponding to the fundamental frequency of the range code. Using this technique, the laboratory measured peak-to-peak error was about 1 ns during station calibration and 0.6 ns with the MVM '73 transponder. The system configured to 1 MHz also exhibited less sensitivity, in terms of range error to different transmitter modulators.

The logical continuation of these tests was to try the technique with a spacecraft. As discussed in the next subsection, the Voyager Project provided the spacecraft.

C. Voyager Navigation Requirements

During the summer of 1978 it became apparent that some difficulty was being experienced in meeting the 4.5 $\sqrt{2}$-meter interstation range accuracy requirement of the Voyager Project. Ranging of this precision was required to assure adequate navigation margins during the Voyager Saturn encounter. During the period immediately prior to the encounter, the spacecraft will be near zero declination where Doppler will not provide angle data of sufficient precision to navigate the encounter.

Accurate navigation is jeopardized by large range biases which had been observed between DSN stations. Even between conjoint, i.e., almost colocated, stations, biases were on the order of 4 meters. It was decided that the Mu2, with its higher

precision ranging and full dual channel capability, could be used to investigate the problem.

III. Preliminary Results

The results to date are encouraging, but far from complete. Upon completion of the experiments, a full report will be published in *The DSN Progress Report*.

A. Viking Radio Science

It was hoped that some definite results could be given at this time. Unfortunately, the solar corona was extremely noisy during the January, 1979, conjunction. This created a problem in that the DSN receivers could not maintain carrier phase lock with the spacecraft X-band signal when the spacecraft was "two-way". In this mode, the spacecraft downlink (spacecraft to Earth) signal frequencies are related by fixed multiples to the uplink (Earth to spacecraft) S-band signal frequency. For the S-band downlink, the multiple is 240/221 while for X-band it is 880/221.

The corrupting effects of a plasma upon a radio signal are inversely proportional to the square of the signal frequency (Ref. 4). At first glance, then, X-band should be better than S-band. However, in the multiplication of the S-band uplink frequency to X-band, the jitter induced by the solar plasma is increased by the same factor, resulting in a badly distorted signal.

While the S- and X-band range obtained by the Mu2 appears good, the S-band Doppler data is marginal and the X-band Doppler virtually unusable. We had planned to use the S-X two-way Doppler data to interconnect the S-X range data with earlier one-way Doppler data in a scheme to measure and track the solar corona charged particle density. Because of the poor signal conditions, we are forced to a less satisfactory and much more labor-intensive fall back.

Despite these problems, the recent data obtained by the Mu2 is expected to complement and improve the results of the 1976 experiment. A future article will discuss the data processing and tracking operations involved in this latest test of the Theory of General Relativity.

B. Advanced Radiometric Research

The data from the Mu2 at DSS 43 is corroborating the experiments reported by Layland, et al. (Ref. 3). Figure 1 is a graph of range residuals taken from observations of the Voyager 1 spacecraft at DSS 43. Less than a 30-minute gap separated PRA and Mu2 measurements. Not only is the Mu2 data less scattered but the PRA data seems to have a bimodality. Such a signature is possible due to wave form distortion.

Table 1 summarizes a representative sample of data drawn from the comparison plotted in Fig. 1 and from normal Voyager 1 tracking operations. The data are given as RMS scatter about a line fit to the range residuals. A linear fit is used since errors in the ephemeris or ionosphere model appear linear over a short span. While the Mu2 data appears "raw," the PRA residuals are shown both raw and corrected by the second point of "DRVID" (Difference Ranged Versus Integrated Doppler) measured after each range acquisition. Data from the Mu2 has about one-fifth of the scatter of the raw PRA data and one-third that of the DRVID-corrected PRA data.

Correcting the PRA data by DRVID involves extra computation and requires that temporal charged particle variation in the ray-path be small. It is difficult to distinguish the signature of a plasma event and the error imposed by wave-form distortion. On the basis of these findings, we have proposed that the DSN upgrade the PRA to utilize a 1-MHz high-frequency code.

C. Voyager Navigation Requirements

It is too soon to report any results from the investigation into the interstation range bias. The bias between DSS 42 and DSS 43 varied from 6 meters to 2.5 meters during the period April, 1978, through early January, 1979. During a Voyager navigation cycle, it was observed that no bias existed when the Mu2 was used at DSS 43 and the PRA at DSS 42. Other than pointing out the sensitivity of these biases to ground equipment variation, no further conclusions are justified at this time.

The Voyager navigation cycle consists of continuous tracking of a Voyager spacecraft for a period of about 48 hours. Ranging and Doppler data are taken in turn from each of the 64-meter stations in the DSN. As appropriate, some 26-meter stations are also sampled. Figure 2, which is taken from Ref. 5, shows the range residuals from a Voyager navigation cycle in late January 1979. The numbers in circles indicate the tracking station used. (DSS 42/43 are at Tidbinbilla, Australia; DSS 63 is at Robeledo, Spain; and DSS 12/14 are at Goldstone, California). The vertical lines indicate the bias between stations as determined from linear fits to the respective data sets. Note that the bias between Spain and California is smaller than that between the two Goldstone stations. Also, the lower scatter due to the use of the Mu2 at DSS 43 is readily apparent.

By the time this article is published, several experiments should have been performed testing various theories as to the cause of the interstation bias. These will involve both DSS 42 and DSS 43 in an interchange of equipment during Voyager tracking.

IV. Modifications to the Mu2

In this section, we present the modifications effected on the Mu2 software and hardware to accommodate installation at the conjoint Australian stations and to incorporate the filtered range code correlation algorithm into the operational software.

A. Hardware

When the Mu2 was last installed in the DSN (at DSS 14), the ranging interface with the High-Speed Data Line was via a computer known as the Tracking Data Handler (TDH). When the DSN was upgraded for the Voyager era, the TDH was replaced by the Metric Data Assembly (MDA). While the TDH was only one-way, processing output data, the MDA is two-way, also routing operator supplied parameters and commands from the so-called "host" computer to the ranging machine.

Because the Mu2 was installed in a conjoint station, two MDA interfaces were required. Each interface attached directly to the Mu2 data and control lines. The Mu2 uses a simple internal bus scheme which has five address lines, one enable line, two handshake lines and two sets of 16-bit unidirectional data lines. A control circuit board and two identical 14-line interface adapter boards, comprising a total of more than 100 integrated circuits, were installed in the Mu2 Interface Unit.

Besides the computer interfaces, two band-pass filters were required to shape the 10-MHz IF signal prior to detection within the Mu2. These filters are described in Ref. 2. They are ±1.5-MHz-wide with a 10-MHz center frequency. When the phase moduled IF signal is passed through the filters, all harmonics of the 1-MHz range code are greatly attenuated. In effect, a 1 MHz sine wave tone is then detected and correlated in the Mu2. This tone is largely devoid of the wave-form distortion plaguing lower frequency initial codes.

Installation at the conjoint DSS 42/43 required that the Mu2 interface to the Block III receiver at the DSS 42 26-meter station and the Block IV receiver at the DSS 43 64-meter station. The signals supplied by these receivers are compatible except that the Doppler tone which the Block III outputs is half the actual Doppler frequency. Provision for either receiver's Doppler was originally made by using movable straps on the Mu2 Doppler scaler circuit board. This board was modified so that the Mu2 computer could select the proper scaling.

Another change to the Doppler scaler was to allow the computer to configure for X-band or S-band Doppler scaling (they differ by a factor of 11/3). This allowed the DSS 42 ranging to be processed by Mu2 channel 2 which is normally

used for X-band. The arrangement facilitates simultaneous processing of S-band ranging data from both stations.

B. Software

The software which orchestrates the Mu2 has been described in Ref. 1. Only those features saliant to the DSS 42/43 installation will be discussed here. By far the most extensive modification to the software involved deleting the TDH software and adding software to support the MDA. In total, over 1800 changes were made in the Mu2 software to accommodate the DSS 42/43 installation.

One modification to the software involved transferring the sine-wave correlation algorithm from test software to the operational software. The modular construction of the Mu2 programming made this a very straightforward task. Modification was also made to the "mode" parameter to facilitate independently switching the two Mu2 channels between square-wave and sine-wave correlation routines.

A major change in Mu2 control philosophy accompanied the conversion to the MDA. Specifically Mu2 parameters and directives would normally be provided through the MDA rather than from the Mu2 console teletypewriter. The Mu2 uses an operator interface known as Tutorial Input (Ref. 2). Through the foresight of the MDA designers, free-form ASCII text can be transmitted from the MDA to attached devices. Therefore, all commanding could retain the Tutorial Input format. It was necessary only to place data blocks from the MDA into the Tutorial Input buffer.

Additional control capability had to be added to specify which MDA (i.e., which station) was in control. In either case, primary, or overriding, control remained with the console teletype. Three control commands were assigned only to the teletype. They are:

M/M1   Control from either teletype or MDA1 (DSS 43)

M/M2   Control from either teletype or MDA2 (DSS 42)

M/TTY   Control only from teletype

After program initialization, control may either be specified at the teletype or it will be assumed by the first MDA to "talk" to the Mu2. Control is returned to "unassigned" by using the release command M/REL.

The Viking era Mu2 had two interrupt buttons; one to start range acquisitions, the other to attract the computer's attention for commanding. Remote control of the Mu2 necessitated a new command, M/ACQ, to start acquisitions. In order to use the console teletype for commanding, the PDP-11 computer now monitors the teletype for a line-feed character. Upon

receipt of line-feed, teletype commanding is initiated. The two interrupt levels freed with these two changes were immediately absorbed by the MDA interface.

A workable control concept would be useless without a means for outputting data. The MDA provides the data pathway. Each second, the MDA expects a range data block of 35 words (Ref. 7). This block reports both parameters used to obtain the ranging and the range measurements including correlation voltages, DRVID, and power- to-noise estimates.

Within the block, the ranging system outputs Universal Time Coordinated (UTC). There is also a field for data validity. When this field indicates "new" data, the word containing UTC is interpreted as is a time tag for the data. In a break with the PRA philosophy, the Mu2 always sets the time tag to the appropriate data time. The MDA can then be late in sampling the block and still obtain the correct sample time.

As described in Ref. 1, the Mu2 software is modular. Three new modules were added to interface to the MDA and the TDH module was removed. Four thousand words of core memory were added to the PDP-11 to contain the new subroutines. The first module, the MDA data output module, is enabled by the system scheduler to output range data each second. This is done in background, as is all data handling, to prevent time conflicts. Upon completing the output sequence, the module enables MDA data input by initializing an appropriate time tag in the scheduler. The subsequent transfer from the MDA to the Mu2 contains either operator directives or a blank block.

After these two transfers are completed, the scheduler is again enabled to allow a second Mu2 to MDA transfer. This block contains information to be displayed on the station operator's CRT screen. The display can either be routine data, a list of operator supplied parameters, status messages, or alarm messages.

Three of the five available displays are associated with operator-supplied parameters. Display 1 shows the current default parameters. These are the parameters directly changed by operator input. At transmit time for a new range acquisition, the default parameters are copied into the transmit parameter buffer and also stored in the receive parameter circular buffer. The transmit parameters can be observed in display 2. After one round-trip-light-time (an operator-supplied parameter) has elapsed, receive parameters are transferred from the circular buffer to the receive parameter list. This list is presented in display 3.

It is because of the receive parameter circular buffer that each range acquisition done by the Mu2 is completely independent of any other acquisition. Hence, parameters can be changed at any time without affecting any acquisitions already in space.

Displays 4 and 5 are used to observe and analyze data quality. The ranging correlation voltages appear on display 4. As explained in the Mu2 technical report (Ref. 1), these voltages are a direct and immediate indicator of range quality. An indirect quality indicator, DRVID is presented on display 5. This display is mainly used during pre- and post-track range calibrations. The actual range measured and the epoch time (TO) appear on both displays.

Some problems arose in debugging the new software with the MDA. These were manifest as large numbers of parity errors in the transfers between the MDA and the Mu2. It appeared that there were timing conflicts within the MDA. The situation is aggrevated because most MDA activity occurs immediately after the station one second timing pulse. The problem was solved by delaying the transmission of the Mu2 range data block to 0.1 second, and the transmission of the display block to 0.5 seconds after the one-second pulse.

V. The Future

Several more experiments are planned for the near future into the interstation range bias problem. Other than these tests, the Mu2 will continue to be the prime ranging machine at DSS 43. At the present time, it is planned to remove the Mu2 on or about 1 October 1979. We hope to install it at DSS 13 for continuing experiments with Viking Lander 1 and research into automatic, "unattended," ranging.

Acknowledgements

References

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Table 1. Mu2/PRA Comparison

Date	DSS-43 Mu2	DSS-43 PRA RAW/DRVID	DSS-14 PRA RAW/DRVID	DSS-63 PRA RAW/DRVID
5 Jan. 1979	7.8	4.25/3.96		
7 Feb. 1979	1.99			8.12/5.10
8 Feb. 1979	0.52		5.81/1.64	
17 Feb. 1979	1.36		4.24/2.60	4.82/3.00

Number indicates RMS scatter in Range Units about a linear fit to the range residuals.
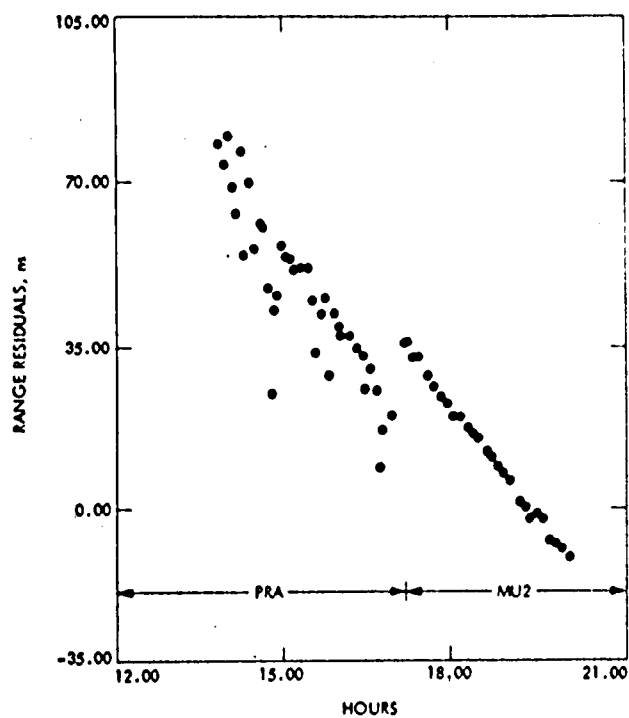

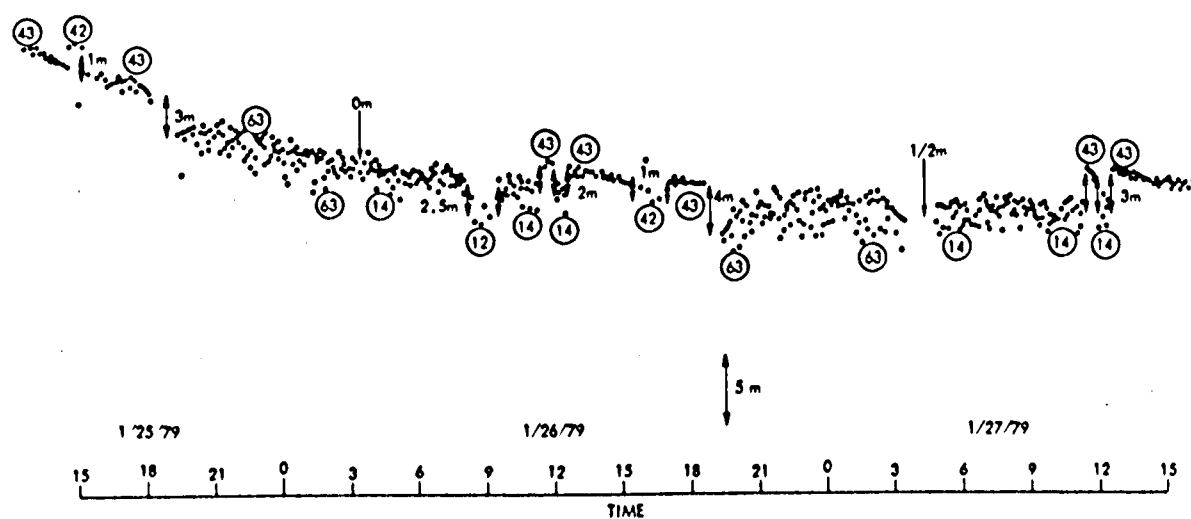**Fig. 1. Range residuals from the 5 January 1979 Mu2/PRA comparison test using Voyager 1**

Fig. 2. Voyager 1 navigation cycle residuals