S-Band Receiver Third-Order Loop Demonstration

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In mid-April 1972, the Mariner Mars 1971 spacecraft began encountering high
doppler rates under weak signal conditions. The Block III receiver was dropping
lock, resulting in lost data. This article describes a third-order tracking filter which
was designed for the Block III receiver and successfully demonstrated at DSS 14.

I. Introduction

The Mariner Mars 1971 spacecraft has pushed the DSIF
tracking system into a new era. Currently, the mission
dynamics are such that S-band doppler rates of 25 Hz/s
and doppler acceleration as high as 0.16 Hz/s have been
experienced. The Block III DSIF receiver cannot track
doppler rates greater than 10 Hz/s with the current signal
margin (8 dB).

It was decided to design and build a third-order loop
filter for the Block III DSIF receiver. The receiver using
the third-order loop has two bandwidths (5 and 10 Hz)
and is capable of tracking doppler rates in excess of
1000 Hz/s and will stay locked with doppler acceleration
as high as 3.8 Hz/s² as demonstrated by tests at CTA 21
(see Fig. 1).

The immediate response from DSS 14 operations was
that the third-order loop solved the tracking problem. It
was noted, however, that the initial frequency acquisition
was more difficult. A trip was made by the designer to
DSS 14 to watch an operational acquisition of the Mariner
Mars 1971 spacecraft with the third-order loop. It was
apparent that part of the problem was the operator’s con-
tinuous tuning of the voltage-controlled oscillator (VCO).
While this procedure has worked well for the second-
order loops, it is inappropriate for the third-order loop due
to the added “memory” inherent in the added integrator.

It was found that when the third-order loop was within
200 Hz (at S-band) that loop would acquire within 60
seconds. When frequency predicts were used, acquisition
occurred within 15 seconds.

Acquisition with the high doppler rates (i.e., 30 Hz/s
present when the uplink is being swept) is a more difficult
problem. This appears to be too great a doppler rate for an
unassisted acquisition, even for a third-order loop. This
presents a problem since the receiver operator has no good
indicators of when he is “oversteering” the third-order loop,
and acquisition under these conditions seems unreliable.

The answer to the problem seems to be a hybrid loop—
a device that can acquire as a second-order loop and
automatically switch to the third-order configuration to
track. A filter of this type has been designed and tested at
CTA 21 (see Fig. 2).
II. Design Approach

A. Third-Order Loop Filter

The open-loop transfer of the third-order loop filter (see Fig. 1) is

\[
H(s) = \left( \frac{R_2 + R_3}{R_1} \left( \frac{1 + SC}{R_2 + R_4} \right) \right)^2 
\approx \left( \frac{R_2 + R_3}{R_1} \left( 1 + SC R_3 \right) \right)^2 
= \left( K_1 \frac{(1 + T_2 S)}{1 + T_1 S} \right)^2
\]

The design approach has been to select the design that satisfied the doppler and doppler rate input with the minimum time constant \( T_1 \).

Define

\[
q = \alpha \Lambda K_d (\text{volts/deg}) K_v (\text{Hz/volt}) K_m 
\times 360 \times \left( \frac{K_2}{T_2} \right)^2 T_2 = KK_1^2 \frac{T_2}{T_1} = G \frac{T_2}{T_1}
\]

\[
q_0 = 6.75
\]

\[
W_{L_0} = \frac{4.455}{T_2}
\]

\[
W_L = q \frac{2q + 3}{2T_2 (2q - 1)}
\]

\[
\phi_{ss} (\text{deg}) = \frac{360(\Omega_0 + \Delta t)}{G} + \frac{720\Delta T_1}{G} + \frac{360\Delta T_2}{G}
\]

Let

\[
a = \frac{360 T_2^3}{q}
\]

so that

\[
T_1 = \frac{a \Lambda}{\phi_{ss}} + \left( \frac{a \Lambda}{\phi_{ss}} \right)^2 + \frac{a (\Omega_0 + \Delta t)}{\phi_{ss}} \right)^\frac{1}{2} = R_1 C
\]

\[
T_2 = \frac{4.455}{W_{L_0}} = R_1 C
\]

\[
R_1 = R_2 \left( \frac{R_2 + R_3}{R_3} \right) \frac{\sqrt{K T_2}}{q}
\]

B. Second-Order Hybrid Filter

Design for the hybrid loop was implemented by leaving the second integrator (see Fig. 2) as designed for the third-order loop (since this integrator stores the frequency offset control voltage to the VCO). The first integrator was modified to be a simple gain stage so that the second-order loop would have the same bandwidth as the third-order loop. The second-order loop is overdamped (i.e., \( \tau_0 = 7.91 \)).

For second-order hybrid design,

\[
H(s) = \frac{R_4}{R_1} \times \frac{R_2 + R_3}{R_1} \left( \frac{1 + \frac{R_1 R_2}{R_3 + R_4} SC}{1 + SC R_3} \right)
\approx \frac{R_4}{R_1} \times \frac{R_2 + R_3}{R_1} \left( 1 + SC R_3 \right)
= K_1 K_2 \left( \frac{1 + T_2 S}{1 + T_1 S} \right)
\]

\[
r = 360 K_0 (\text{volts/deg}) K_v (\text{Hz/volt}) K_m \alpha K_1 K_2 \frac{T_2}{T_1}
\]

\[
= G K_1 K_2 \frac{T_2}{T_1}
\]

\[
K_1 = \frac{2T_2 \times W_{L_0} - 1}{G \times \frac{R_2}{R_1} \times T_2}
\]

but

\[
R_1 = R_2 \left( \frac{R_2 + R_3}{R_2} \right) \frac{\sqrt{K T_2}}{q} \quad \text{(same as standard third-order loop design)}
\]

\[
R_1 = K_1 R_2
\]

Whenever \( R_2 << R_3 \),

\[
r = G K_1 R_2 + R_3 \times \frac{R_2 C}{R_3 C} \times T_2 \approx G K_1 \frac{R_2}{R_1} T_2
\]

and

\[
W_{L_0} = \frac{r + 1}{2T_2}
\]

so that

Computer programs have been written for both of the above designs utilizing the PDP-11 BASIC language.

III. Future Effort

Theoretically the acquisition characteristics for the third-order loop are much superior to the second-order
loop (and may well prove to be the case when computer-controlled acquisition is available). However, in the present DSS 14 environment, it appears the hybrid loop is a better approach since it allows past experience and procedures to be used during difficult manual acquisition and then automatic switching (activated by the lock detector circuit) to use the superior tracking performance of the third-order filter. Theoretical studies are currently underway to predict the loop performance to an arbitrary forcing function.
Fig. 1. Third-order filter

Fig. 2. Second-order hybrid filter