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CONSCAN Implementation for Antenna Control Assembly

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CONSCAN was previously recommended for implementation in the Antenna Control Assembly. This article presents specifics of this implementation, including calibration, signal cleanup, and system protection. Equations for programming the algorithms are provided.

I. Introduction

Reference 1 discussed the merits of several automatic tracking techniques, and concluded that CONSCAN (conical-scan tracking) was most desirable for DSN antenna application.

Additional effort was necessary to develop the equations and algorithms required for the implementation of CONSCAN. This article provides that detail as the final phase of the study involving automatic tracking techniques for the Antenna Control Assembly (ACA).

This report presents the detailed analysis and instructions for implementing CONSCAN into the ACA.

II. CONSCAN Algorithm

Scan deviation may be defined as deviation of the antenna beam axis from the antenna boresight axis. The deviation is resolved into two orthogonal components called elevation and cross-elevation. Let

$E(k)$ = elevation deviation

$X(k)$ = cross-elevation deviation

$A(k)$ = azimuth deviation (or hour-angle deviation)

E_{ANT} = antenna elevation (or declination)

A_{ANT} = antenna azimuth

To maintain cross-elevation deviation constant with elevation, the azimuth deviation must vary with elevation angle:

$$A(k) = X(k) \sec E_{ANT} \tag{1}$$

From Fig. 1, the scan equations are

$$E(k) = R \sin \omega k \Delta \tag{2}$$

$$X(k) = R \cos \omega k \Delta \tag{3}$$

where

ω = scan rate in rad/s

= $2\pi/P$

P = scan period, s

R = scan radius, deg (Fig. 1)

k = no. of units of Δ (constant)

Δ = time between updates (for data samples)

Hence, having chosen the time between updates, and indexing time by the number k, the scan deviation may readily be computed.

III. Antenna Pointing Angle Equations

The components of the antenna pointing angles, E_{ANT}, and A_{ANT} are calculated for two cases, CONSCAN *OFF* and *ON*. (Refer to Fig. 2)

(1) With CONSCAN *OFF*,

$$E_{ANT}(k) = E_{PRED}(k) + E_{TAB}(k) + S_E \tag{4}$$

$$A_{ANT}(k) = A_{PRED}(k) + A_{TAB}(k) + S_A \tag{5}$$

where the subscripts are

ANT = actual antenna command

$PRED$ = predicted value from ephemerides

TAB = value from systematic error correction table

and where,

S_E = total correction for elevation

S_A = total correction for azimuth

= $S_X \sec E(k)$

S_X = total correction for cross-elevation

(2) With CONSCAN *ON*,

$$E_{ANT}(k) = E_{PRED} + E_{TAB}(k) + S_E + E_C(k) \tag{6}$$

$$A_{ANT}(k) = A_{PRED} + A_{TAB}(k) + S_A + A_C(k)$$

$$= A_{PRED} + A_{TAB}(k) + S_A + X_C(k) \sec E_{ANT} \tag{7}$$

where E_c and X_c are the latest (kth) correction in elevation and cross-elevation, respectively. The predicts for azimuth and elevation are calculated from the spacecraft ephemeris or from the known location of a radio star. The Correction Table is a set of stored corrections and provides a first-order correction to previously measured systematic errors.

IV. Coordinate Correction Algorithm

Reference 2 derives the expressions for corrections in each coordinate. These corrections are given in integral form, but are modified to conform to digital processing requirements by expressing them in summation form as follows,

$$E_C = G \sum_{SCAN\ k} V(k) \sin(\omega k\Delta + Z) \tag{8}$$

$$X_C = G \sum_{SCAN\ k} V(k) \cos(\omega k\Delta + Z) \tag{9}$$

where $V(k)$ is the kth edited signal sample,

G = gain

Z = phase shift

The phase shift Z is required because of mechanical phase lag of the antenna response and the phase lag of the AGC or radiometer averaging. The gain G and the phase shift Z must be calibrated for each antenna configuration and signal source.

The values of E_C and X_C may be determined by one of the following approaches:

(1) Brute Force correlation.

(2) Fast Fourier transform.

The Brute Force approach is simple and is indicated by the nature of expression. All that is needed is use of a sine and cosine lookup table, multiplication, and accumulation.

The fast Fourier transform (FFT), although it requires more computations, provides more information as a bonus.

Analytically, the resultant correction parameter Y, having two components X_C and E_C, is expressed as

$$Y = X_C + jE_C \tag{10}$$

where j is the square root of -1. If we use Eqs. (8) and (9) and DeMoivres theorem,

$$Y = G \sum V(k)\, e^{j(\omega k\Delta + Z)}$$

$$= Ge^{jZ} \sum V(k)\, e^{j\omega k\Delta} \tag{11}$$

This is the $Y(1)$ term of the discrete Fourier transform, generally computed by the FFT. The transform is

$$Y(N) = Ge^{jZ} \sum V(k)\, e^{jN\omega k\Delta} \tag{12}$$

The term $Y(1)$ gives pointing error. All terms for $N > 1$ are a measure of anomalies. For example, ellipticity in the antenna beam will give a very small but finite contribution to $Y(2)$. Normally, all $Y(N)$ for $N \geqslant 2$ will be very small because $V(k)$ is usually nearly constant. When $V(k)$ has a glitch due to receiver dropout, interference, or a step change of signal such as a spacecraft transmitter mode change, then $Y(N)$ for $N \geqslant 2$ can be much larger than $Y(1)$. Thresholding can be done on a few values of $Y(N)$ to detect anomalous conditions in order to reject potentially absurd calculated "corrections."

The number of signal samples per scan must be chosen to be a power of 2 in order to directly use the FFT. For example, the conveniently sized 512-point FFT provides a scan of 51.2 s when a signal sample rate of 10 Hz is used.

The steps followed in using the FFT are:

(1) Using the $V(k)$ values for a scan, calculate $Y(N)$ by performing the above summation (Eq. 12), for several values of N, say 2, 3, and 4.

(2) Compare each $Y(N)$ thus computed to preselected threshold. If the threshold is exceeded, the correction for this scan is rejected. The threshold that is chosen should be small; it should be on the order of the scan radius. However, it should be large enough to allow the second harmonic generated as a result of elliptic cross section of the beam to be ignored. The rejection rate due to glitches and other spurious content of $Y(N)$ should be less than 5 percent.

V. Tracking Signal Cleanup and Protection During Track

Reference 1 proposed signal cleanup and protection schemes both for radio sources and spacecraft.

The signal inputs are (1) square law detector output for radio sources and (2) AGC (Automatic Gain Control) voltage for spacecraft tracking. The anomalies that are likely to occur that will affect the received signal power may be listed as follows:

(1) Signal dropout due to momentary receiver dropout (out-of-lock), operator error or some unexpected transient (glitch) in the receiving system.

(2) Change in spacecraft transmitter or antenna mode.

(3) Spacecraft antenna pointing direction change with spacecraft limit cycling, or some other change on board the spacecraft causing variation in the downlink signal strength.

(4) In the case of spin-stabilized spacecraft, modulation in the signal level due to spin rate.

Testing is a very essential part of signal processing. Since the data processing requirements are low and the penalty for spacecraft data loss is high, tests should be made as frequently as possible.

When tracking radio sources, a single receiver dropout should cause a scan correction to be skipped. Further, expected signal level should be compared to observed AGC level as another check. AGC can be calibrated at known signal levels, and/or by feeding the expected signal level to ACA. The apparent signal level is continuously compared with the expected (predicted) signal level, and, if deviation is greater than 1 or 2 dB, that scan is rejected.

However, if there is a slow cycling of signal level, a straight line connecting the last and the first point may be subtracted to determine the difference in signal level.

Hence, ignore scan if

$$|\, V(k) - \text{expected } V(k)\, | \geqslant \text{threshold} \tag{13}$$

This is the condition of *out of lock*; if cycling (low) is expected, the straight line test referred to above is analytically expressed as,

$$\left| V(k) - \frac{V(k_o) - V(0)}{(k_o)}\, k - V(0) \right| \geqslant Th \tag{14}$$

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where

Th = threshold (1 or 2 dB)

k_o = number of points in scan

For testing of radio source tracking anomalies, the system temperature and the expected radio source temperature should be provided so a check can be run. This will entail a precise setup for the radiometer gain to ensure accurate comparisons. A table of temperatures for common radio stars could be easily stored into the system memory.

If T_{op} is the system operating temperature and T_s the radio source (expected) temperature, the scan should be ignored if

$$\text{scaled } [V(k)] < T_{op} \tag{15}$$

or

$$\text{scaled } [V(k)] > T_{op} + T_s + \text{margin} \tag{16}$$

There is the very real likelihood that, even though signal level is continuously and carefully tested, an unusually large correction may sneak through. Thus limit tests become necessary. These may be categorized as first limit and second limit.

(1) First limit: If the desired correction exceeds the first limit, correction only to the extent of the limit value is to be made. Examples of limits that could be set as first limits on elevation and cross-elevation are

   (a) For S-band, 0.015 deg

   (b) For X-band, 0.005 deg

   If the next correction has to be the same limit (because it is equaled or exceeded), no correction should be made; instead, a warning is generated.

(2) Second limit: If the desired correction exceeds the second limit, no correction is made; instead, a warning is generated. Example limits for elevation and cross-elevation that could be set are

   (a) For S-band, 0.030 deg

   (b) For X-band, 0.010 deg

VI. Antenna and Signal Source Gain and Phase Calibration

Referring to Eqs. (8) and (9), we see the gain parameter is given by G. At this time, an expression for G will be derived to enable calibration.

The closed loop time constant T is given by (Ref. 2)

$$\mathrm{T} = -P/\ln r \tag{17}$$

Define

$$r = 1 - hA \tag{18}$$

where h in Ref. 2 has been defined as "selectable" gain and $P = 2\pi/\omega m$.

A is a parameter readily measurable by use of expressions 11 through 21 (Ref. 2). Equation (19) of Ref. 2 expresses it as (for radiometer)

$$A = CBT_s g'(R)P/2 \tag{19}$$

where C is a constant representing receiver gain, and B is the effective band width:

$$B = \frac{\left[\int_0^\infty |H(f)|^2\, df\right]^2}{\int_0^\infty |H(f)|^4\, df} \tag{20}$$

with $|H(f)|^2$ the power gain, and

$$g'(R) = \left.\frac{dg(\beta)}{d\beta}\right|_{\beta=R} = \left.\frac{d}{d\beta}\, e^{-\mu\beta^2/w^2}\right|_{\beta=R}$$

$$= -2\,\frac{\mu R}{w^2}\, e^{-\mu R^2/w^2}$$

$$= -2\,\frac{\mu R}{w^2} \tag{21}$$

R as used above is the scan radius and w is the antenna beamwidth between half power points.

$$\mu = 4 \ln 2 = 2.773 \tag{22}$$

From Eq. (18) above,

$$\ln r = \ln(1 - hA) \cong -hA \tag{23}$$

substituting in Eq. (17),

$$\mathrm{T} = P/hA \tag{24}$$

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Thus, expressing $G = h\Delta$ after dropping the negative sign,

$$G\,(\text{radiometer}) = \frac{\Delta w^2}{\mu CBT\; T_s R} \tag{25}$$

For spacecraft, Ref. 2 (Eq. 101) has

$$A = \frac{k' P \mu R}{2w^2} \tag{26}$$

where k' is found by calibration of the AGC slope.

By using Eq. (25) and $G = h\Delta$,

$$G\,(\text{spacecraft}) = \frac{2\Delta w^2}{k' \mu TR} \tag{27}$$

k' may be calculated by using the derivation for fast AGC in Ref. 3, where in Eq. (12), the expression to be used is

$$V_{AGC} = \frac{1}{\alpha} \ln v(t) \tag{28}$$

where $v(t)$ is the normalized voltage gain (Eq. (63), Ref. 2),

$$\alpha = \frac{1}{k'} \tag{29}$$

with R^2, θ^2, $\phi^2 << w^2$ (Eq. (63), Ref. 2) using Eq. (91) of Ref. 2, and Eq. (26) above,

$$E_C = h\,\frac{\mu RP\,\phi_k}{2\alpha w^2} \tag{30}$$

α is given in Eq. (3) of Ref. 3, and ϕ_k is the symbol for elevation (cross-elevation) deviation in the kth scan.

$$8.686\,\alpha = \text{slope in dB/volt} = S$$

or

$$k' = 1/\alpha = 8.686/S \tag{31}$$

Equation (27) above can be rewritten by substituting k' from Eq. (31) above, and $\mu = 2.773$

$$G = 0.0830S\,\frac{\Delta w^2}{R} \tag{32}$$

We will now discuss phase-shift calibration. Equations (8), (9), and (11) above include the phase term Z. The phase shift is needed because

(1) For radio source tracking, filtering in the radiometer causes a phase lag.

(2) There is a filtering effect of AGC, during spacecraft tracking.

(3) Phase lag of the antenna is a function of the scan period, e.g., for a 64-meter antenna (Ref. 2) and

(a) For a 28-s scan, $Z = -30$ deg

(b) For a 58-s scan, $Z = -15$ deg

The required value of Z may be measured by the following means:

(1) Assuming a nominal value of Z, CONSCAN the antenna to achieve boresight.

(2) Open the control loop, and offset the antenna in one axis only, say cross-elevation.

(3) If the nominal Z is correct, the correlation and hence the indicated correction will be nonzero in only the offset axis.

(4) If Z is incorrect (i.e., if correlation is nonzero in both the axes), the correction for Z for the case of cross-elevation offset is:

$$\Delta Z = \tan^{-1} \frac{\text{elevation correction}}{\text{cross-elevation correction}}$$

$$= \tan^{-1} \frac{E_C(k)}{X_C(k)}$$

If the fast Fourier transform (FFT) is used for signal processing, the phase angle of the fundamental output $Y(1)$ is exactly ΔZ.

VII. Signal Source Acquisition Policy

Predicted offset from boresight is expected to be within 10 dB (X-band) initially. As this raises the possibility of large anomalies, a spiral scan for acquisition is recommended.

To attain higher accuracy in initial acquisition, three parameters should be established.

(1) Beamwidth B in which acquisition is highly likely.

(2) Time T necessary to make a decision.

(3) Size of the search region.

The procedure for initial acquisition is as follows (Fig. 3):

(1) Dwell at best guess for T seconds.

(2) Move out $B/2$ in one axis.

(3) Dwell at that position for T seconds.

(4) Traverse spiral until the search is complete (the spiral is discussed below).

(5) Set the scanner at the point of maximum signal level. Alternatively, one may stop when any signal is found; but this may be a side lobe.

The spiral search is done by arguing that for every 2π increase in θ there should be an increase in R by B, i.e.,

$$\frac{dR}{B} = \frac{d\theta}{2\pi} \tag{33}$$

The coordinate system is shown in Fig. 3a.

If the scan rate is $\dot{\theta}$, at R radius of scan velocity is,

$$\text{velocity} = R\,\dot{\theta} \tag{34}$$

so if in T seconds the beam has moved by an amount B, then

$$(R\dot{\theta})\,T = B \tag{35}$$

solving Eqs. (33) and (35), we have

$$R(t) = \sqrt{R_0^2 + \frac{B_t^2}{\pi T}} \tag{36}$$

$$\phi(t) = \frac{2\pi}{B}\,[R(t) - R(0)] \tag{37}$$

where

$$\theta(0) = 0;\ R(0) = R_o$$

Another maybe simpler way to a solution is to implement Eq. (35) directly. Every T seconds, command a change in θ at the rate

$$\frac{\Delta\theta}{\Delta t} = \frac{B}{RT} \tag{38}$$

with $\Delta t = T$,

$$\Delta\theta = \frac{B}{RT}\,T = \frac{B}{R} \tag{39}$$

Using Eq. (33) now and substituting Eq. (39), we have

$$\Delta R = \frac{B}{2\pi}\,\Delta\theta = \frac{B^2}{2\pi R} \tag{40}$$

The response to commands every T seconds can be prevented from being jerky by choosing T/N intervals instead of T, with N such that smoothness results. Simultaneously, $\Delta\theta$ and ΔR quantities can be attained in N steps.

VIII. Conclusions

This report is intended to be the final one as regards investigation into CONSCAN and treatment of appropriate algorithms for signal cleanup and limit tests to assure its maximum accuracy and desirability.

The treatment described herein is designed to lead to development of software for CONSCAN antenna operation including K band. Summarizing the recommended techniques to be employed in conjunction with CONSCAN:

(1) For initial acquisition, employ stepped spiral search.

(2) Employ continued and incessant testing of [illegible] to verify:

(a) In-lock.

(b) Reasonable in level.

(c) Within limits.

(3) Use FFT for signal processing if feasible, as it provides more tests and insight into existence of glitches and spurious content of the input signal level.

References

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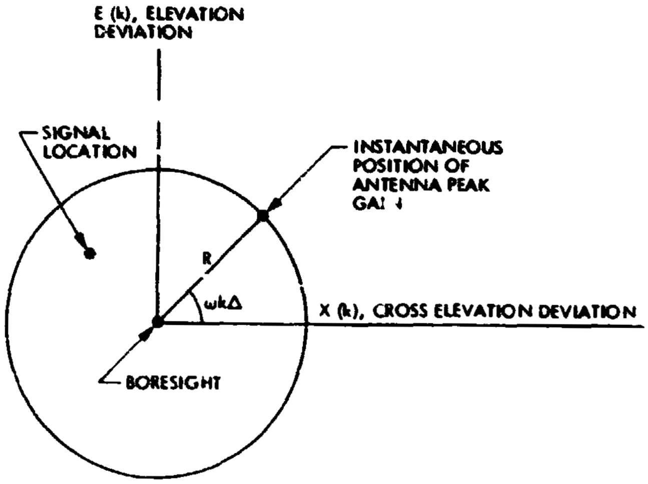

Fig. 1. Scan radius defined

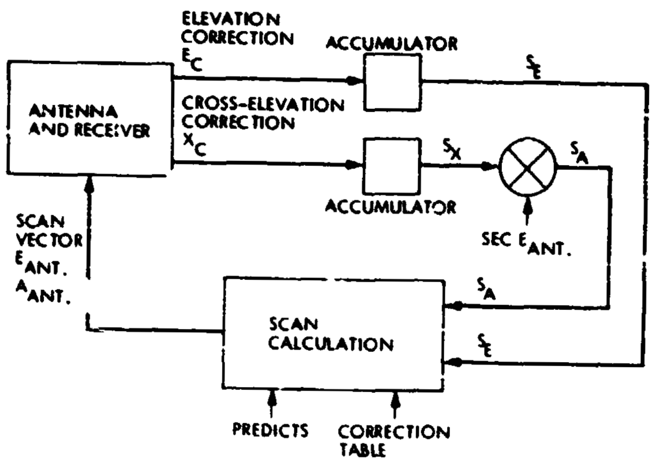

Fig. 2. Block diagram of CONSCAN pointing

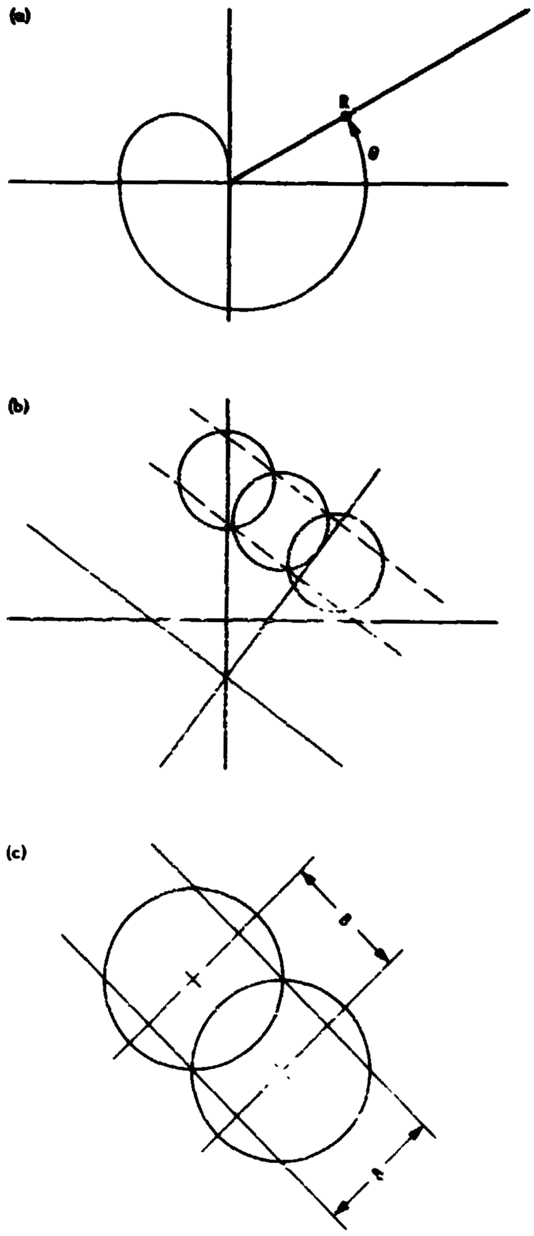

Fig. 3. Spiral acquisition scan geometry: (a) spiral scanning; (b) N-step scan; (c) scan sweep