Receiver Design Concepts for ΔVLBI and Differential One-Way Range

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This report describes three alternative structures for the receiving instrument for wideband spacecraft ΔVLBI or differential one-way range navigation. It does not contain a fully definitive analysis of this subject. Rather, it is intended to introduce to the reader ways of thinking about the ΔVLBI instrument that are more closely related to a conventional spacecraft instrument than to a radio-science VLBI instrument.

I. Introduction

This report describes three alternative structures for the receiving instrument for wideband spacecraft ΔVLBI or differential one-way range navigation. It does not contain a fully definitive analysis of this subject. Rather, it is intended to introduce to the reader ways of thinking about the ΔVLBI instrument that are more closely related to a conventional spacecraft instrument than to a radio-science VLBI instrument. While it is true that this radio-science VLBI instrument can be augmented to detect the spacecraft tones, this approach designs-in some errors which can be avoided by a more direct approach toward the spacecraft signal detection part of ΔVLBI navigation. A much more complete error analysis should, of course, be invoked in the process of designing the actual ΔVLBI navigation instrument.

In wideband ΔVLBI navigation, differential delay measurements to two tracking stations are alternately made between a natural radio source (quasar) and a spacecraft (Ref. 1). The quasar is assumed to be far enough away that it is absolutely immobile within the celestial coordinate system. Its position may be precisely known as well. The quasar observations calibrate (or partially calibrate) the relative station clocks, station delays, propagation medium delays, and Earth platform orientation. The spacecraft observation, corrected by this calibration-by-quasar, effects a measure of the angular separation between the spacecraft and quasar. An appropriate series of such observations will measure the vector separation between spacecraft and quasar in the plane of the sky.

Differential one-way ranging is a weakened form of ΔVLBI, wherein the calibrating quasar observations and the spacecraft observations are widely separated in time or spatial orientation, such that much of the commonality of propagation medium delays and platform orientation is lost. Only the commonality of clocks and receiver delays is retained, perhaps degraded by significant drifts with time or other environmental factors.

One of the principal concerns in the design of an instrument for wideband ΔVLBI is that the electrical path lengths through that instrument not be different for the spacecraft signals and the quasar noise. We could have greatly diminished this concern by making the spacecraft emit a narrowband noise signal, and processing it on the ground in a manner identical to the quasar signal processing. Such a tactic, however, in quite reasonable circumstance, requires either an astonishingly strong signal from the spacecraft or an impossibly long integration time. Consequently, it is expected that the wideband signals emanating from a spacecraft for ΔVLBI use will be of a nature such that they can be coherently detected at each station. In particular, the precision-defining signal is expected to be a sine wave modulated at low level onto the spacecraft carrier. Having chosen to let the signals from the spacecraft and the detection process for it differ in character from the quasar signals, and their detection, it is incumbent upon the instrument designer to avoid letting the difference result in a differential delay error.

II. The Conventional VLBI Instrument

The conventional radio-science VLBI instrument could be used to sample and record the spacecraft signals for subsequent detection. Figure 1 shows a functional overview of this instrument, and the first stage of processing the spacecraft signal from it. A "phase calibrator" provides the fundamental timing reference for this system (Ref. 2). The IF mixer and SSB down-converters are used to bring the pertinent components of the spacecraft signal to baseband where they are filtered, hardlimited, sampled, and recorded. The hardlimiting of the sampled data causes a 2-dB loss in SNR, but its use in the spacecraft signal path acts to keep the electrical path length the same as for the quasar signals. Extraction of the spacecraft and phase-calibrator tones from the sampled data could as well take place in real-time without recording, and would effect a considerable reduction in the number of bits needed to characterize these signals. This factor will be important when the ΔVLBI data are to be shipped to JPL via data lines instead of by mailing tapes. Only short-duration correlation sums would be generated in real-time, with the more complex phase tracking process being deferred to where it can be performed at leisure.

Tracking of the phase-calibrater tones is relatively straightforward because they are very slowly varying and vary over a limited range corresponding to the delay variations of the receiving instrument itself. Use of the phase-calibration tones in VLBI on natural radio sources has previously been described in detail (Refs. 3 and 4). Their use with spacecraft signals is similar. The measured phase-shift of the calibration tones which results from passing through the receiver is combined with such detailed information as exists on phase-shift ripples in the receiver, to produce an estimate of the receiver phase-shift at the frequency of the embedded spacecraft tone. The correlation sums for the spacecraft tone are then corrected for this estimated receiver phase-shift to produce a sequence of correlation sums as they would exist at the calibrator-injection point using a "perfect" phase reference.

Tracking of the spacecraft tones from their correlation sums is complicated by doppler effects, and by spectral spreading. The carrier tone can be phase-tracked relative to predicts to produce a delay-rate estimate akin to conventional doppler. The bandwidth of this tracking need only be narrow enough to produce a strong SNR, and should be comparable to the bandwidth of the conventional carrier tracking loop. The signal strength of the precision-defining tones is sufficiently lower than that of the carrier that they very likely cannot be tracked directly. We are interested, however, only in the group delay of this signal, which appears as the phase differences between the upper and lower precision-defining tones. This phase difference is much narrower and more slowly varying than the individual tones, and can thus be tracked at a bandwidth appropriate to detecting this lower-strength signal. Quadrature-component correlation sums for the phase difference between either precision-defining tone and the carrier can be directly computed from the quadrature correlation sums of the carrier and the appropriate tone. This computation incurs virtually no loss in SNR as long as the SNR for the correlation sums of the carrier tone is at least moderate (e.g., 3-10). These carrier side-tone phase differences are also narrowband and can be tracked to a bandwidth at which the SNR will permit a lossless computation of the phase difference between the upper- and lower-precision-defining tones. Tracking of the other side tones provided to resolve the ambiguities of the precision-defining tones would proceed similarly.

Many of the instrumental error sources which one would anticipate here are common mode between the quasar signals and spacecraft signals processed as described above. Closely spaced phase ripples in the receiver passband, such as those designed into the single-sideband demodulator, are one apparent source of non-common-mode errors. For a concrete example, assume an SSB demodulator with logarithmically spaced ripples of ±5-degree magnitude (Ref. 5). If the spacing between precision-defining tones is 40 MHz, one such 5-degree phase error would cause a group-delay error of 1/3 ns or 10 cm. In computing the differential one-way range between two stations, there is not one but four opportunities to suffer this 5-degree phase shift – one at each station on each of the upper- and lower-precision-defining tones. Thus, a probable (RSS) error of 20 cm or a worst-case error of 40 cm results, relative to the average channel phase.

If the same local reference frequencies are used to down-convert the quasar signals and the spacecraft signals, the quasar signals intrinsically average the channel phase, and the calibration tones serve only to carry this information along through the processing. This is true only as long as the calibrations are applied identically to the quasar and spacecraft signal processing. An interesting thing happens if we attempt to improve accuracy by using a wider spanned bandwidth for the quasar signals than for spacecraft signals, in that now the phase calibrator is an essential part of the connection between quasar delay and spacecraft delay. We now have four *more* opportunities for a 5-degree phase shift to occur – on the calibration tones in each channel. The (unlikely) worst-case error is thus raised to 80 cm!

The above discussion assumes that we admit to no knowledge of these designed-in phase ripples, whereas we do know at least their intended characteristics. Some numerical calculations have been performed using the demodulator simulation models used previously on quasar VLBI (Ref. 3), and the assumption of a 5 percent manufacturing tolerance for the physical filters. The calculated worst-case error reduced to 15-20 cm for this condition. We could alleviate the need for a model by reducing the limits on the allowed phase ripple to well below the ±5 degrees, but manufacturing tolerances could still induce errors that were a sizeable fraction of one ns (30 cm).

III. A Range Demodulator

A coherent detection receiver like the DSN receiver with a range demodulator could be used to detect the spacecraft tones, provided only that a suitably accountable reference signal can be generated. The phase of the received range signal is measured relative to this reference signal, so that the absolute specification of the received signal phase includes that of the reference signal. A digitally controlled oscillator/synthesizer (e.g., the DANA DIGIPHASE SYNTHESIZER with modification) appears to be capable of generating within its range an arbitrary sine wave with "absolutely" known phase. This knowledge of phase is described by the digital phase numbers in the synthesizer control logic, and the timing signals with which that logic operates. These timing signals should be generated as directly as possible from the tracking station's primary frequency standard in order to minimize the errors in the knowledge of phase. Figure 2 shows a rough block diagram of the envisioned range demodulator. The phase-locked loop of the DSN receiver will track the phase of the received spacecraft carrier, thus enabling coherent detection of the precision-defining sideband signals. Doppler information from this carrier tracking, or doppler predict information, is used to adjust the phase of the reference signal generator so that the signal integration can continue long enough to obtain a strong (30-60 dB) SNR. The primary group delay path for this signal is through the low noise amplifier, the IF down-converter, the reference signal mixers, and the reference signal generator/synthesizer to the station timing standard. Ancillary errors can come into the system through DC offsets or gain imbalances in the demodulator channels, but can be reduced to an almost negligible level by time-multiplexing the roles of the demodulator channels as was done in the MU-I ranging system (Ref. 6).

The range demodulator can be easily augmented as shown in Fig. 2 to be a DSB down-converter and recorder for VLBI signals. In doing VLBI recording, the code reference generator is programmed to correct for Earth-rate doppler predicts. This way, the primary group-delay path is through the code reference generator to the station time standard, with little contribution from the low-pass signal channels. The sampling times for the quadrature channel samples should be displaced by one-half a sample interval from the in-phase channel samples to limit the time delay offset between corresponding samples at the two stations, and thus limit the corresponding SNR degradation.

The DSB demodulator channels do not have the designed in-phase ripples that are characteristic of the SSB channels, but their low-pass filters can have curvature to their phase characteristics so that the average channel phase shift as perceived via the quasar noise signals is not the same as the phase shift perceived by the spacecraft signals. The effect should be small, but needs to be analyzed.

As a ΔVLBI instrument, the principal errors seem likely to occur within the reference signal generator (synthesizer). These may be drifts resulting from environmental changes, or they may be systematic phase delay errors that depend upon the frequency at which the synthesizer is operating, or upon start-up transients. The number of distinct circuit elements which are critical to the reference timing in a continuous-time sense is not large, and the complexity of the logic necessary to avoid gross systematic errors is also not large. Therefore, there seems to be no intrinsic reason why the reference sine wave could not be generated with a reference phase which was accurate to a small part of a nanosecond in its time origin. We do *not* presently know if any existing commercially available synthesizers will perform as needed.

As a differenced one-way ranging instrument, additional errors result from drifts in the receiver and cable delays which are relatively slow compared to the time intervals between quasar and spacecraft observations in ΔVLBI, but which are significant over several hours. Such drifts are suspected to be on the order of a nanosecond. They could be largely eliminated if the delay of the receiving system were measured during or prior to both quasar and spacecraft observations. A device like the VLBI "phase" calibrator could provide the necessary signals at the receiver inputs. Calibration during the spacecraft signal observation risks cross-talk errors between signals. Calibration prior to each observation creates operational complexity unless event sequencing is performed automatically. Drifts in the time standard itself may make calibration of the receiver delays irrelevant. For instance, if 24 hours elapse between calibration of the clocks by quasar and a one-way range observation, the clock uncertainty alone is around 1 ns if the station reference has a 10^{-14} stability.

This same basic instrument could be used as the receiving portion of a two-way ranging instrument. The transmitting code reference signals could be generated by a synthesizer identical to that used in the receiving side. Whatever systematic errors existing in the setting of the reference signal phase are now committed twice in one station, instead of once in each of two stations in the differenced one-way/ΔVLBI mode. Doppler corrections can be programmed into the receiver reference signal phase in a "fully" accountable fashion. A sequence of sine waves of related frequencies can be generated by the synthesizers in very much the same manner as sequential components are generated by the present ranging systems (Refs. 6 and 7). A suitable computer and control program is needed to drive the reference synthesizer through their desired sequence of events, and to untangle the phase measurement into a range measure.

The resulting machine provides more flexibility than is needed for two-way ranging, but offers commonality with the one-way range instrument, and may offer an increased precision in the accountability for phase of doppler correction. The principal error contribution is probably in the instrument drifts between calibration (pre-pass) and measurement time, and timing standard drifts during the range signal round-trip propagation time. These again are of the order of 1 ns, unless real-time calibration or other control techniques are applied.

IV. Digital Demodulation

One way to minimize the growth of errors in a precise system is to concentrate as much as possible the precision-defining element of the system into one "basket" – and then very carefully control that "basket." If, for example, the received signal is sampled and digitized at some fairly wideband point in the IF stream of the receiver, only this sampler, and the parts of the receiver ahead of it, can effect delay errors (cf Fig. 3). The reference signal generator, mixers, and demodulator channels have been deleted as continuous-time error sources, because they operate only on sampled data. When elements such as these do not work, they should fail in a clear and visible way, rather than with a degraded delay precision. Such elements should, in fact, be able to be designed for intrinsic failure detection, if desired. The MU-II ranging system was a successful proof-of-concept for digital demodulation techniques, using the 10-MHz IF stream (Ref. 7).

The sampler/digitizer converts the received signals from the continuous-time domain to a sample stream whose timing is completely defined by the station's frequency standard and clock system. Several types of error are possible. The connection between sampler and timing system can admit time-base errors – amplifier/buffer delays, etc. Digital signals can feed back through the digitizer and affect the apparent analog level input unless the digitizer is carefully isolated. Hysteresis in the threshold elements of the digitizer can effect modulation phase biases that vary by as much as 0.01 rn., which implies differenced delay errors on the order of 0.1 ns for a 20-MHz signal. To achieve this modulation bandwidth, the IF that is sampled has to be at least at 50-55 MHz with a sampling frequency of four times that being desirable for convenient signal processing. With some care in design, the variability of the effective sampling instant should be able to be held to a fraction of a nanosecond for the circuitry that can sample at this speed.

The reference signal generator is a fairly complex module if done completely digitally. We could as an alternate develop the reference signal with a synthesizer, as in Fig. 2, and immediately sample and hardlimit it. We admit in this way some additional continuous-time errors, which depend upon the circuitry used.

System and time-base calibration of the digital instrument can be done by quasar observing like the Burst-Sampler VLBI clock-sync system (Ref. 8). This technique is affected by the average group delay of the receiver passband, which may differ by several nanoseconds from the effective delay imposed upon the 20-MHz sine wave modulation anticipated from the spacecraft. This effect of the receiver passband can be eliminated if we know what it is precisely. One obvious way to measure the receiver characteristic is to use a device like the VLBI "phase calibrator," acting at high signal level, as a pulse train with which to probe the impulse response of the receiver. The actual measurement is obtained from the digitized IF samples by accumulating samples over the pulse repetition interval (Ref. 9). This passband measurement could be performed as part of the pre-pass checkout, and admit errors on the order of a nanosecond from receiver delay drift over several hours. It could be performed immediately adjacent to each observation of quasar or spacecraft and eliminate such drift as an error source, but at the cost of a more complex operational sequence.

System calibration can also be done by quasar observing with the digital counterpart of the DSB system of Fig. 2. In this case, the part of the quasar signal that passes through the digital channel filters has suffered almost the same phase shift from the receiver IF passband as the spacecraft signals, and hence their delays will be largely common mode. The digital filters themselves have a fully accountable phase shift, so the only significant potential error source is receiver IF and sampler/digitizer drifts and aberrations.

V. Ambiguity Resolution

The 20-MHz signal from the spacecraft has a period of about 25 ns. Unless the differential range to this spacecraft is known more precisely than this, other signals from the spacecraft must be used to resolve the 25 ns ambiguity. If performed digitally within the sampled-data time base, Costas loop tracking of the telemetry subcarrier and/or its harmonics can provide this ambiguity resolution, with or without telemetry on that subcarrier. This tracking is not particularly difficult, being similar to that which must be performed to extract telemetry data bits from the spacecraft signals. Performing it digitally ensures the accountability of phase/delay relative to the sampler time base, thus making it a feasible estimator for the differenced range.

Analog Costas loop tracking of the telemetry subcarrier or its harmonics can also be an ambiguity resolving detector for any of the configurations, with some care. The differential delay through the receiver to the subcarrier reference point versus through the receiver to the reference point for the precision-defining tones must be known much more accurately than the 25-ns ambiguity that needs resolving. The phase of the tracking VCO must be absolutely accounted for with respect to the same time base as the other spacecraft tones are detected. This arises naturally if the tracking VCO is in fact a digital synthesizer as used in the Fig. 2 configuration for the precision-defining tones.

The most obvious way to resolve the ambiguity does not use the telemetry signal, but adds to the spacecraft additional modulation tones which are a subharmonic of the precision-defining tones. With any of the configurations, detection of these tones is identical to detection of the precision-defining tones. It is performed either via additional hardware channels or by time-multiplexing the use of a minimal set of channels. The current expectation is that such tones as needed will be available on the spacecraft carrying the wideband ΔVLBI beacon.

VI. Summary

This report contains a very subjective discussion of three possible receiver structures for wideband spacecraft ΔVLBI. It is not a definitive analysis of any one of them, but should be treated as background material for the design of the "right" ΔVLBI instrument. Each of the instruments described here has some advantages relative to the others.

Instrumental errors on any of the ΔVLBI receivers appear to easily approach or exceed 1 ns (30 cm). Design of an instrument with a goal of better than 10-cm accuracy should be quite a challenge.

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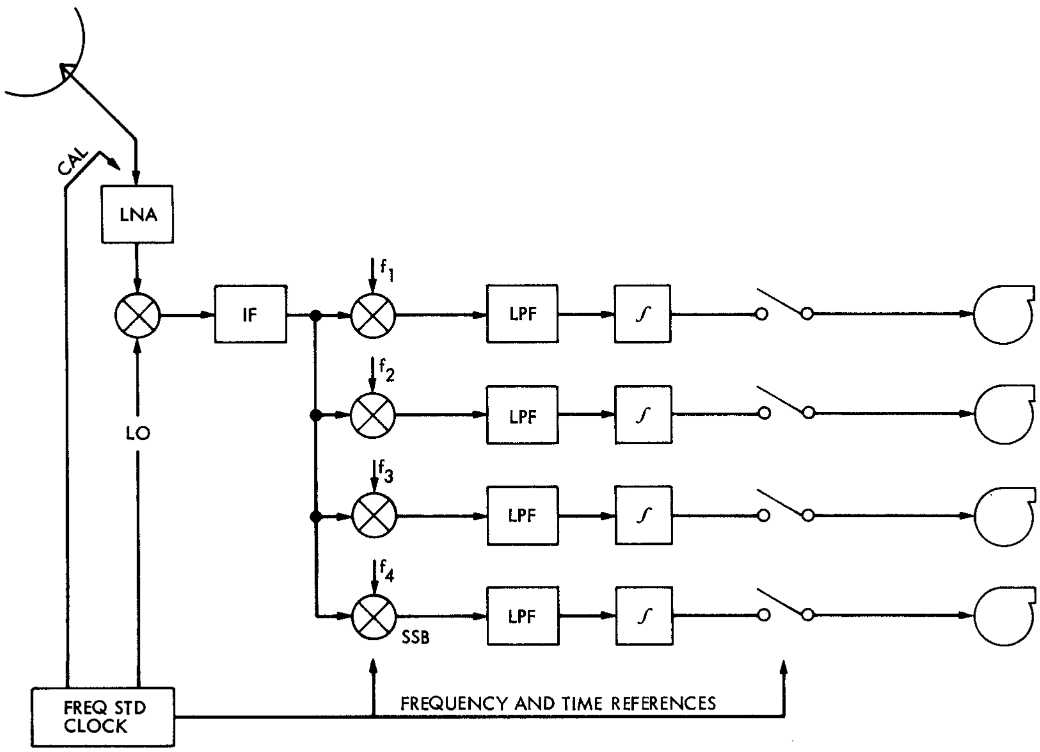

SEPARATE CHANNELS RECORD CARRIER, UPPER- AND LOWER-EDGE TONES AND AMBIGUITY-RESOLVING TONE

CALIBRATOR EFFECTS THE PRECISE TIME BASE

Fig. 1a. Functional diagram of radio-science VLBI instrument

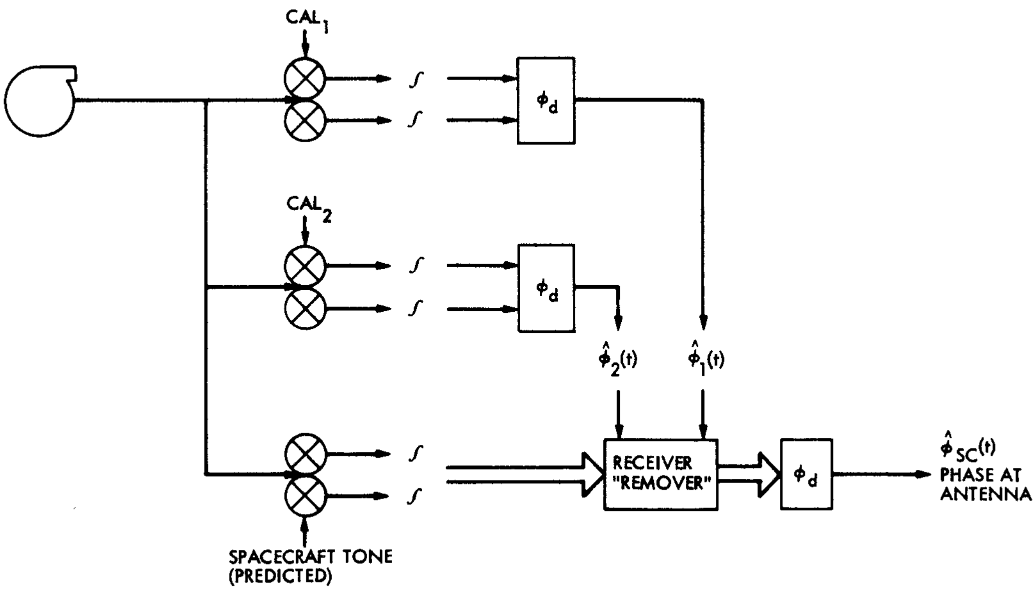

Fig. 1b. Functional diagram of spacecraft signal extraction from each VLBI channel

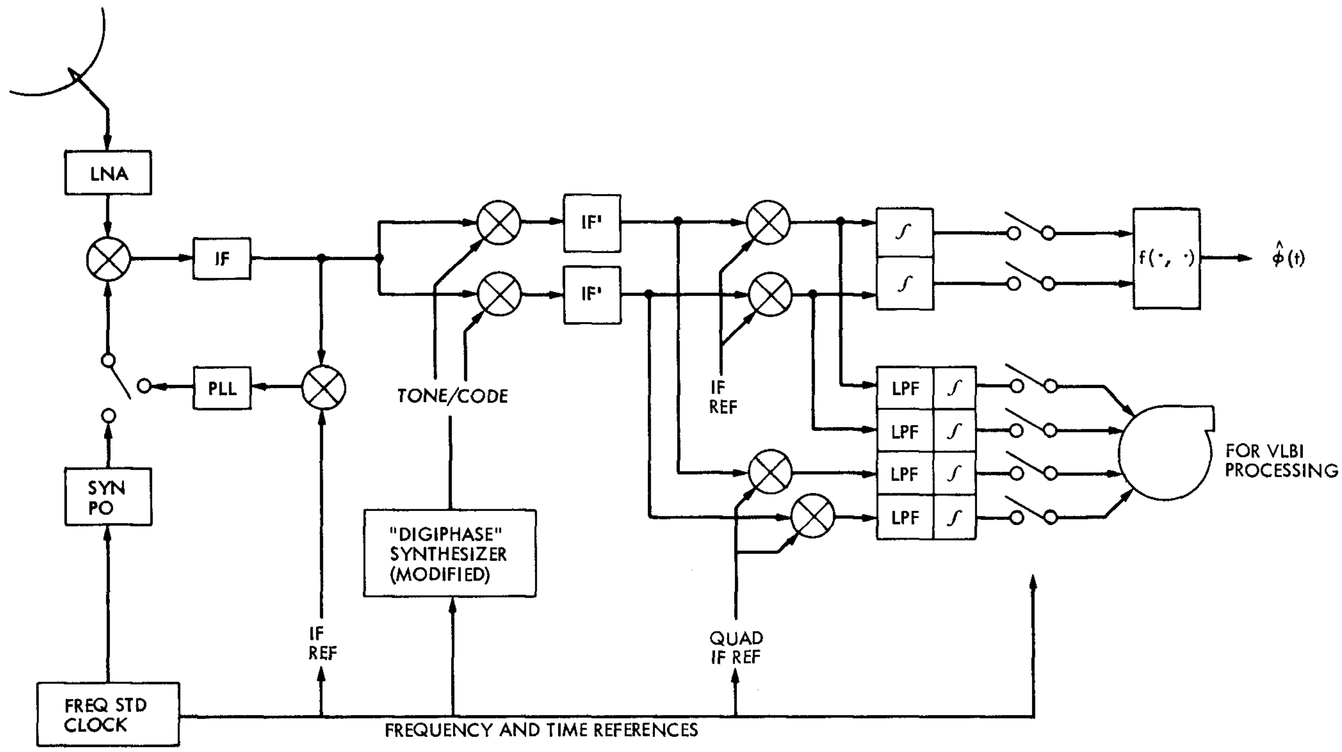

Fig. 2. Functional diagram of range demodulator and DSB VLBI receiver

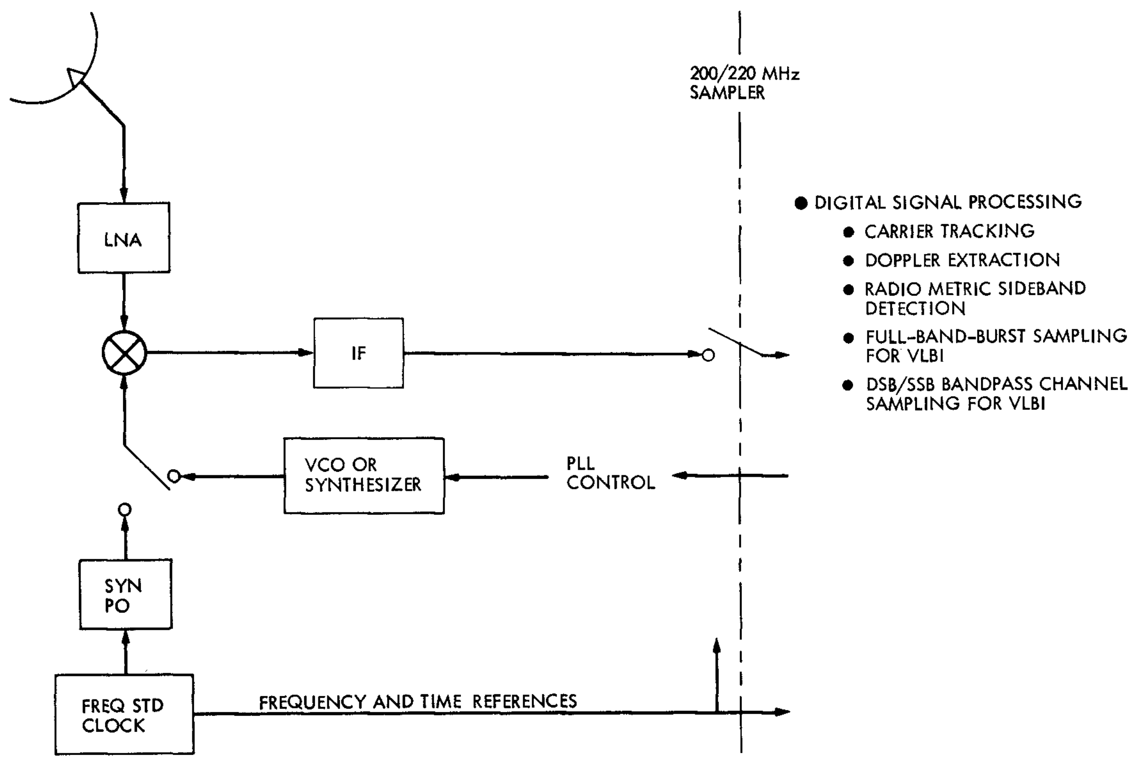

Fig. 3. Concept for digital radio metric receiver