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An Architecture for the Electronics of an Uplink Array

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Using a phased array of antennas on the ground to transmit signals to a distant spacecraft requires a method for keeping the carrier phases properly aligned at the separate antennas. One approach is to implement a receiving capability at each antenna along with the transmitting capability, and to use measurements of the relative phases of received signals to align those of the transmitted signals. This can be effective if phase errors are similar in the two directions. An architecture that facilitates this approach is proposed.

I. Introduction

This article describes a high-level block diagram for the electronics of an array of antennas that includes the ability to transmit (uplink) data to a distant spacecraft. The same array might simultaneously receive (downlink) data from the same spacecraft, or it might be dedicated to the transmitting direction with separate antennas being used for receiving. In either case, the transmitting array must include a receiving capability to assist in its calibration.

The design described here is based on an operating concept in which the transmitter carrier phases at the antennas are kept in alignment by measuring the delays on the receiving signal paths and using that information to correct the transmitting path delays. The difference in delay between the transmitting and receiving paths is assumed to have been separately calibrated. The design is intended to ensure that the path difference remains relatively stable, so that the latter calibration can be infrequent (once per day or less).

II. Description

Figure 1 is an overall block diagram of the system. It consists of

(1) A radio frequency (RF) assembly at each antenna, including frequency upconversion for transmitting and downconversion for receiving

(2) Analog signal transmission on optical fiber between each antenna and a central processing facility

(3) At the central facility, conversion of signals to or from digital form and digital signal processing

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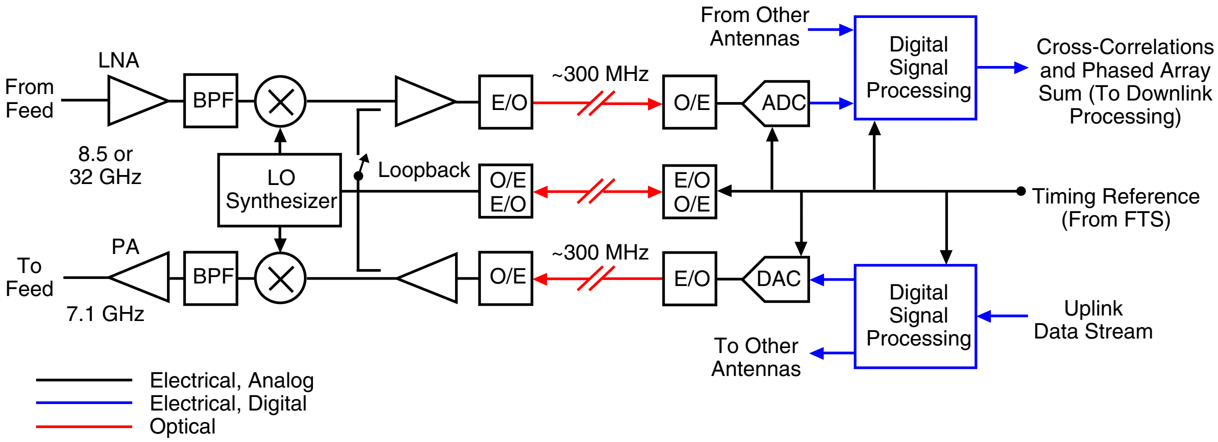

Fig. 1. Top-level block diagram of uplink array electronics, showing transmit and receive signal processing for one antenna. (Here E/O and O/E are electrical-to-optical and optical-to-electrical converters, and FTS is the frequency and timing system.)

A. Analog Electronics

A basic feature of this configuration is that the analog portions of the transmitting and receiving signal paths use common components as much as possible and are otherwise as similar as possible. The high-frequency components, which contribute most to any phase instability, are confined to a compact assembly at the antennas, with the signal transmission taking place at a relatively low intermediate frequency (IF) and at the same center frequency in both directions. This requires that frequency conversions take place at the antennas. The necessary local oscillators are synthesized for both receiving and transmitting from the same references, distributed from the center on optical fiber.

Any delay change on the reference transmission path will affect the phase of both the transmitted and received signals, but not by the same amount since the local oscillator (LO) frequencies normally are different. To allow them to track as much as possible, the frequency conversions should use the same side band (upper or lower) in both directions. Delay changes on the reference path are likely to be the most sensitive source of system phase errors, and for that reason it is important that the reference path delay be stabilized. This is done by transmitting the reference signals in both directions and adjusting the outgoing phase so that the two-way phase change is constant. (Details of this are not shown in Fig. 1.)

The fiber length from the central building to the furthest antenna is likely to exceed 1 km, and typical fiber has a temperature coefficient of delay around 7 ppm/C. The fiber should be buried over most of its length, keeping temperature changes small, but some of it must be above ground; over long time periods (weeks) even the buried portion suffers significant temperature change. This means that allowance should be made for changes of up to about 0.1 m. To avoid any phase ambiguity on the round-trip phase control, the references should include a signal at 1 GHz or less. The performance of the reference transmission system will be best if only fixed-frequency signals are transmitted. This is feasible, but the details of the design are beyond the scope of this article.

Assuming that the LO references are stable, consider other sources of variation of the phase difference between the transmitting and receiving paths. It should easily be possible to match the physical lengths of the transmit and receive fibers within 100 mm and their electrical lengths within 500 mm (if operating at nearly the same optical carrier wavelength). For a change in each length of 100 ppm, the change in the difference is about 50 μm. At 300 MHz, this corresponds to 7×10^{-5} cycle of phase, which is negligible. It should be possible, though it seems unnecessary, to transmit in both directions on the same fiber. It is feasible to use an IF considerably higher than 300 MHz while keeping the difference in phase variation very small, provided that the same frequency is used in both directions.

The remaining components that are different for transmitting and receiving can have different phase and delay drifts. These include the amplifiers, mixers, optical transmitters and receivers, and the analog-to-digital converters (ADCs) and digital-to-analog converters (DACs), as well as those parts of the LO synthesizer that are different for transmit and receive. In all these cases, we can take advantage of the fact that the components are small and localized to ensure that they are stable. The antenna-based components (with the possible exception of the transmit power amplifier) can all be built into a compact assembly that is mechanically stable, tightly enclosed, and actively maintained at a constant temperature. On a typical conventional antenna (not beam waveguide), the assembly would be near the main reflector's vertex and would move as the antenna is pointed, but it would have no internal moving parts or flexible cables—only the optical fibers need pass through the antenna's rotation axes. The central analog components include only the ADC, DAC, and optical converters; these too can be in a stable, compact assembly. We can rely on such designs and related good engineering practices to ensure that the differential phase and delay drift is small and slowly varying. A reasonable goal is to achieve a maximum differential drift rate of 0.5 ps per hour (1.3-deg phase per hour at 7.15 GHz). This would allow an operating strategy in which the differential delay and phase need not be recalibrated during a 10-hour tracking pass.

It may or may not be feasible to include the power amplifier (PA) in the compact front-end assembly, depending on the power level at which it operates. Compact solid-state amplifiers with up to 50-W output at 7.1 GHz are available commercially now, and this is sufficient for the foreseeable future if transmitters are placed on hundreds of 12-m antennas. If much larger power is needed, as will be the case if only a few antennas are equipped with transmitters, then the amplifier might need to be mounted remotely and additional cables or waveguide might be involved, or new and more efficient amplifiers might need to be developed. In that case, there is a higher risk of not achieving the stability goal.

If the receiving path is used for spacecraft data downlinks as well as for calibration of the transmitting path, then the low-noise amplifier (LNA) and its feed may need to be cryogenically cooled. While that makes the front-end assembly somewhat larger and more complicated, it does not preclude making it stable. Indeed, the cryogenically cooled components are in an especially stable environment.

B. Digital Signal Processing

Figure 2 shows additional details of the central signal processing.

One possible architecture for the receive direction processing is shown. It is described here only briefly because this article focuses on the transmitting side. The received IF can span a bandwidth of $\sim$500 MHz. The full bandwidth is first digitized, then passed through a first-in, first-out (FIFO) buffer that allows coarse alignment of the timing to track the array geometry and compensate for the antenna-specific signal path length. It is then broken into a large number of narrowband subchannels by an analysis filter bank (typically a polyphase filter bank). This allows phase tracking and fine delay tracking to be implemented with a set of complex multipliers and numerically controlled oscillators (NCOs), and it also allows cross-correlation with the other antennas to be accomplished efficiently. If the signal carries spacecraft data, it is then added to the corresponding signals from the other antennas, and then the subchannels are re-synthesized into one wideband channel, producing a "phased array sum" from which the data can be extracted. In parallel, the signal is cross-correlated with those from the other antennas in order to derive the phase and delay error on the downlink path. This information can be fed back in near-real time to the delay FIFO and NCOs of the downlink path of each antenna so as to keep the signals optimally aligned. If an uplink is simultaneously being transmitted, the same information can be used to adjust the uplink signal path provided that the differential delay and phase between uplink and downlink are separately known. The received signal might be broadband noise from a natural source rather than a spacecraft downlink; then the phased array sum normally is not used, but the cross-correlation results still allow the phase and delay errors to be derived.

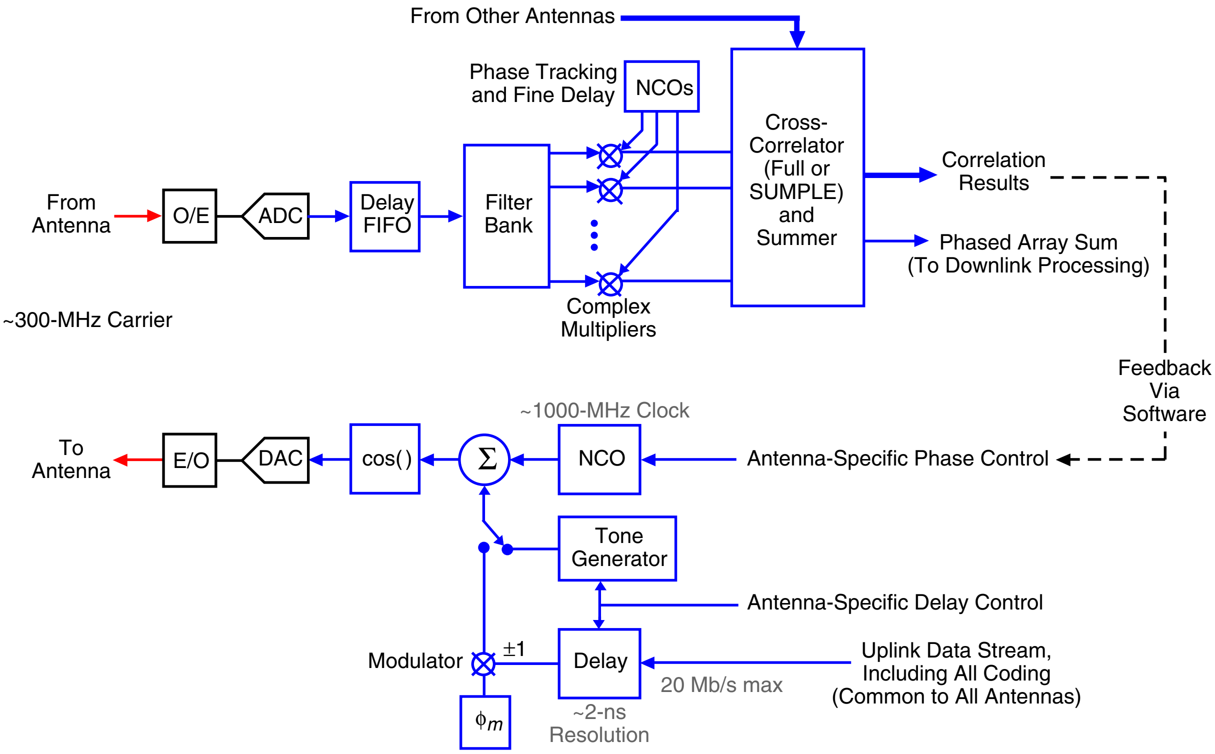

Fig. 2. Further details of the central signal processing.

In the transmitting direction, the signal processing begins with a numerically controlled oscillator that generates the carrier at IF. The NCO is programmed so that its phase versus time tracks the array geometry and compensates for the antenna-specific phase delay of the transmit path. The output of the NCO is a number representing the complete phase $2\pi f_c t + \phi(t)$, where f_c is the nominal carrier frequency (at IF). Digital phase modulation is then applied by adding or subtracting an offset, depending on the current state of the uplink data bit. The uplink data stream is common to all antennas of the array, but the common stream is delayed so as to track the array geometry and to compensate for antenna-specific delay of the transmit path. This delay adjustment needs to be accurate to a small fraction of a bit time, but generally this is much less precise than would be needed if it were also affecting the carrier phase.

The sequence of modulated phase numbers then is converted to a sinusoid via a lookup table representing $\cos(\cdot)$, and that sinusoid is converted to analog form for transmission to the antenna.

Sometimes one desires to impose other kinds of phase modulation on the transmitted signal, such as a sequence of tones for measuring range. In principle such signals could be generated in common for all antennas, but then each antenna would need a more complicated phase-tracking device and a more complicated modulator. To transmit tones, it appears simpler to build a separate tone generator for each antenna as a slow NCO and to program it to include the antenna-specific delay. Range measurement also could be achieved by transmitting pseudo-random bit sequences (PRBS), in which case the PRBS could be generated in common and handled in the same way as uplink data.

III. Discussion

The design allows for the possibility that the transmitting and receiving links are at well separated frequencies (e.g., 7.1 and 32 GHz) or at nearby frequencies (e.g., 34 and 32 GHz). This affects the designs of feeds, antenna optics, and possibly diplexing filters, but not any of the structure shown in Figs. 1 and 2.

As noted earlier, it is important that the center frequency of the IF band used for signal transmission between the antenna and processing center be the same in both directions, but a wide range of frequencies could be used depending on practical considerations. About the lowest feasible choice is 300 MHz, as shown here. This allows a receiving bandwidth of 500 MHz (e.g., 50 to 550 MHz) so as to cover all of the allocation near 32 GHz, and this is in a range that can be digitized relatively easily. It also allows the uplink carrier to be generated directly with an NCO operating at a feasible clock frequency. On the other hand, such a low IF makes the upconversion and downconversion in the front end more difficult because the image-rejecting bandpass filters (BPFs) need to have sharp cutoffs. A sharper cutoff necessarily causes the filters to have a higher temperature coefficient of delay, so that tighter temperature control is needed to meet our stability goal. It may be necessary, therefore, to use a higher IF. This can be done while keeping the speed of the ADC, DAC, and uplink NCO within current feasibility by including another stage of frequency conversion in one or both directions.

For the purpose of establishing data links to distant spacecraft, it is sufficient to know that the signal timing is correctly synchronized among the antennas of the array, so as to maximize the effective collecting area (receive) or radiated power (transmit). Then only the relative timing (differences among antennas) is important, not the absolute delay on any signal path. But for other purposes, especially navigation, the total delay on the two-way path to the spacecraft is important. In our architecture, most of the instrumental part of this delay is in the IF transmission between the center and the antennas. This can be measured easily by providing a loop-back connection from the transmit to the receive path at one or more of the antennas. If this is done at IF (say, from the output of the transmit IF amplifier to the input of the receive IF amplifier), then no frequency translation or other signal processing is needed.

IV. Conclusion

An architecture for the electronics of an uplink array has been proposed. It involves providing both receiving and transmitting capability at each antenna in order to support a calibration stategy that relies on measurements of the receiving signal path to correct for delay changes in the transmitting signal path. By using common or similar components in the two directions as much as possible, delay changes are expected to track closely.