# High-Capacity Communications from Martian Distances Part 4: Assessment of Spacecraft Pointing Accuracy Capabilities Required For Large Ka-Band Reflector Antennas

Dr. Richard E. Hodges, Jet Propulsion Laboratory, 4800 Oak Grove Drive M/S 161-213, Bldg 161, Room 203, Pasadena, CA 91109-8099, Office: 818-354-8851, Fax: 818-393-7144, mailto:Richard.E.Hodges@jpl.nasa.gov

Dr. O. Scott Sands, NASA Glenn Research Center, MS 54-4, 21000 Brookpark Rd. Cleveland, OH 44135, Voice: 216-433-2607, Fax: 216-433-3478, mailto:Obed.S.Sands@nasa.gov

Dr. John Huang, Jet Propulsion Laboratory, 4800 Oak Grove Drive M/S 161-213, Bldg 161, Room 264, Pasadena, CA 91109-8099, Office: 818-354-3586, Fax: 818-393-7144, mailto:John.Huang@jpl.nasa.gov

Dr. Samir (Sam) Bassily, Boeing Satellite Development Center, P.O. Box 92919, M/S W-S12-V333, Los Angeles, CA 90009-2919, Office: 310-364-5970, Fax: 310-416-5656 mailto:samir.bassily@boeing.com

### Abstract

Improved surface accuracy for deployable reflectors has brought with it the possibility of Ka-band reflector antennas with extents on the order of 1000 wavelengths. Such antennas are being considered for high-rate data delivery from planetary distances. To maintain losses at reasonable levels requires a sufficiently capable Attitude Determination and Control System (ADCS) onboard the spacecraft. This paper provides an assessment of currently available ADCS strategies and performance levels. In addition to other issues, specific factors considered include: (1) use of "beaconless" or open loop tracking versus use of a beacon on the Earth side of the link, and (2) selection of fine pointing strategy (body-fixed/spacecraft pointing, reflector pointing or various forms of electronic beam steering). Capabilities of recent spacecraft are discussed.

## 1. Introduction

To achieve a 1 Gb/s data rate for the return link from Mars, a Ka-band system must produce a high level of Effective Isotropic Radiated Power EIRP [1]. This EIRP must be created with a system that has sufficiently low mass and volume so that it can be stowed for launch and transport to Mars. Use of a smaller antenna reduces mass, simplifies stowage and minimizes beam pointing accuracy requirements. However, smaller antennas require much higher transmission power, placing greater demand on the prime DC power generation system (solar cells and batteries). Since large aperture antenna technology reduces the demand for RF power substantially, the development of large deployable antennas promises to reduce overall system mass. Recent developments in deployable antenna technology, such as increased surface accuracy, simplified mechanical design, and extensive field testing offers the possibility of simple, practical Ka-band reflector antennas with extents on the order of 1000 wavelengths at an acceptable mission cost [2, 3].

In cases where the transmit beamwidth is large in relation to the overall pointing error associated with the host spacecraft, antenna pointing can be accomplished though the use of a body-fixed or gimbaled antenna. Pointing of the transmit antenna is accomplished by the sole use of the spacecraft orientation provided by the attitude determination and control system as reference. This is the standard method by which spacecraft communications antennas are pointed. However, if the antenna beamwidth is close to the magnitude of the uncertainty in spacecraft attitude, then pointing losses become excessive. In this case, either the attitude holding capability must be enhanced or the RF communications antenna subsystem must be employed to overcome the large pointing losses. Such RF-based solutions can:

- employ devices in the antenna that sense errors in antenna pointing *or*
- include beam steering not associated with articulating the reflector *or*
- both

The crossover point between spacecraft pointing and RF attitude sensing is set by limiting pointing loss in the link equation. Pointing loss $L_{\text{point}}$ , in dB, is related to the overall (including all sources of error) pointing error $e$ and antenna beamwidth $\theta$ by:

$$L_{\text{point}} = 12\left(\frac{e}{\theta}\right)^2$$

If the pointing loss is limited to no more than a particular value, then the minimum allowable beamwidth can be related to spacecraft pointing accuracy. For a limit of 1 dB pointing loss, the antenna beamwidth must be:

$$\theta > \sqrt{12}e$$

If this condition is not met, then RF sensing of the pointing error must be employed in order to keep the antenna beam pointed at the receiver. Accordingly, a relationship between antenna aperture extent, $D$, and spacecraft pointing error is derived through the direct relationship between aperture extent and beamwidth for aperture antennas:

$$D < \frac{\rho}{\sqrt{12}e}\frac{c}{f}$$

where $\rho$ is the taper factor, $c$ is the speed of light and $f$ is the frequency.

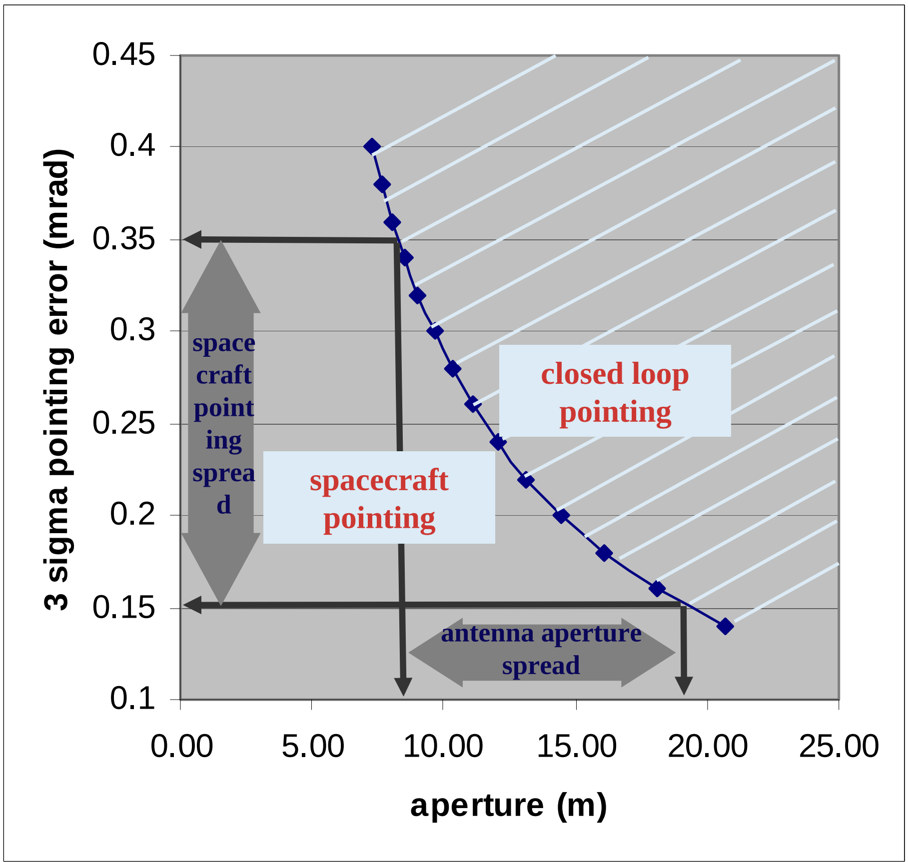


**Figure 1: Spacecraft pointing vs. RF-sensed pointing. Curve indicates limits on antenna aperture and S/C pointing error for spacecraft pointing for a 38 GHz system operating with 1 dB of pointing loss.**

Using a $3\sigma$ value for spacecraft holding threshold (one dimension), and assuming Gaussian deviates, the 1 dB pointing loss is exceeded about 0.54% of the time or slightly less than 8 minutes in 24 hours of operation. The relationship between spacecraft antenna aperture and $3\sigma$ spacecraft pointing accuracy is shown in Figure 1. In this figure the pointing error is taken as the $3\sigma$ spacecraft holding capability, the taper factor is 1.27 (corresponding to parabolic illumination) and the operating frequency is 38 GHz. The region above the curve is the area where closed loop, fine-pointing systems are required. Below the curve, antenna pointing may be achieved using the spacecraft Attitude Determination and Control System (ADCS) alone.

Table 1 [1] specifies typical values for one axis spacecraft attitude holding capability. Spacecraft holding values for current and projected spacecraft are in the range of 0.05 mrad to 1.5 mrad. Note that existing spacecraft such as Cassini are capable of .1 mrad using reaction wheels. If a projection on the spread of $3\sigma$ spacecraft attitude holding capability for future spacecraft is assumed to be between 0.15 and 0.35 mrads, then the associated spread on maximum antenna size is between about 8 and 19 meters. This mapping of the range of values of spacecraft holding capabilities and associated antenna diameters is shown in Figure 1.

**Table 1: Current and projected spacecraft antenna diameters and pointing accuracies**

| spacecraft | reflector diameter (m) | pointing accuracy (3 sigma, mrad) |
|---|---|---|
| MRO | 3.0 | 1.5 |
| MTO (est) | 3.0 | 0.35-0.55 |
| CASSINI | 4.0 | 0.10 (reaction wheel)<br>2.0 (thruster) |
| GOES-N | N/A | 0.05 |
| Aqua R | 1.6 | 0.12 |

Table 1 indicates that it is possible to point an antenna with an extent of 1000 wavelengths using the spacecraft ADCS system alone as a reference. Indeed, a 10-m reflector at 38 GHz requires a $3\sigma$ pointing accuracy of only 0.29 mrads. However, such an analysis is predicated on the assumption that the antenna and associated structure are completely rigid and not affected by on-orbit effects. Note, however, that thermal beam wander can be significant even for rigid reflectors of modest dimensions [4]. For deployable reflectors thermal beam wander can be very large even if the technology chosen for the deployable reflector has a modest Coefficient of Thermal Expansion (CTE). Furthermore, even if the reflector and associated structure could be manufactured so as to eliminate such effects, maintaining the pointing error at very low levels can impose a large burden on spacecraft by way of fuel use and momentum de-saturation procedures. Note that the pointing error of the Cassini spacecraft increases by a factor of 20 in going from reaction wheel operations to thrusters-only operation. Note further that the additional moment and mechanical resonance phenomena associated with such a large reflector and its supporting structure may introduce issues with control authority of the spacecraft over the antenna. In response to these concerns this paper provides an assessment of currently available RF-based pointing strategies as an alternate to spacecraft-only pointing.

## 2. Pointing Options

Traditional spacecraft communications antenna pointing systems rely entirely on devices such as gyroscopes, horizon sensors and/or star tracking cameras to determine the spacecraft's orientation [5]. It is possible, however, to extract attitude information by sensing the direction of the waves coming from the forward/up-link or a narrowband beacon. It is assumed that the return link receiver is, essentially, co-located to the forward/up-link link transmitter or beacon. Such systems typically provide an error signal that is in proportion to the deviation of the antenna pointing direction from the desired direction and are referred to as "closed loop" systems here as the transmit beam pointing direction is determined by the error signal. Systems that do not employ a beacon are referred to as "open loop."

Closed loop systems are capable of measuring only small amounts of deviation from the pointing direction and therefore cannot be used to determine spacecraft orientation in a general sense. However, the error signals generated by such systems are especially relevant to the task of pointing a transmit beam since the error signal can be used directly in a transmit antenna pointing system to direct the transmit beam. Closed loop pointing systems employ an integrated feed for both the forward (receive) and return (transmit) that share the same reflector. Error signals in closed-loop systems are generated with monopulse feeds, offset feeds or other devices that can support Direction of Arrival estimation such as Phased-Array Antennas (PAAs) or multi-beam antennas.

Actuation of the antenna pointing for the return link is accomplished either through the spacecraft ADCS system that controls spacecraft attitude or through mechanical or electrical manipulation of the antenna feed. Figure 2 illustrates examples of ways in which the beam can be articulated through feed manipulation.

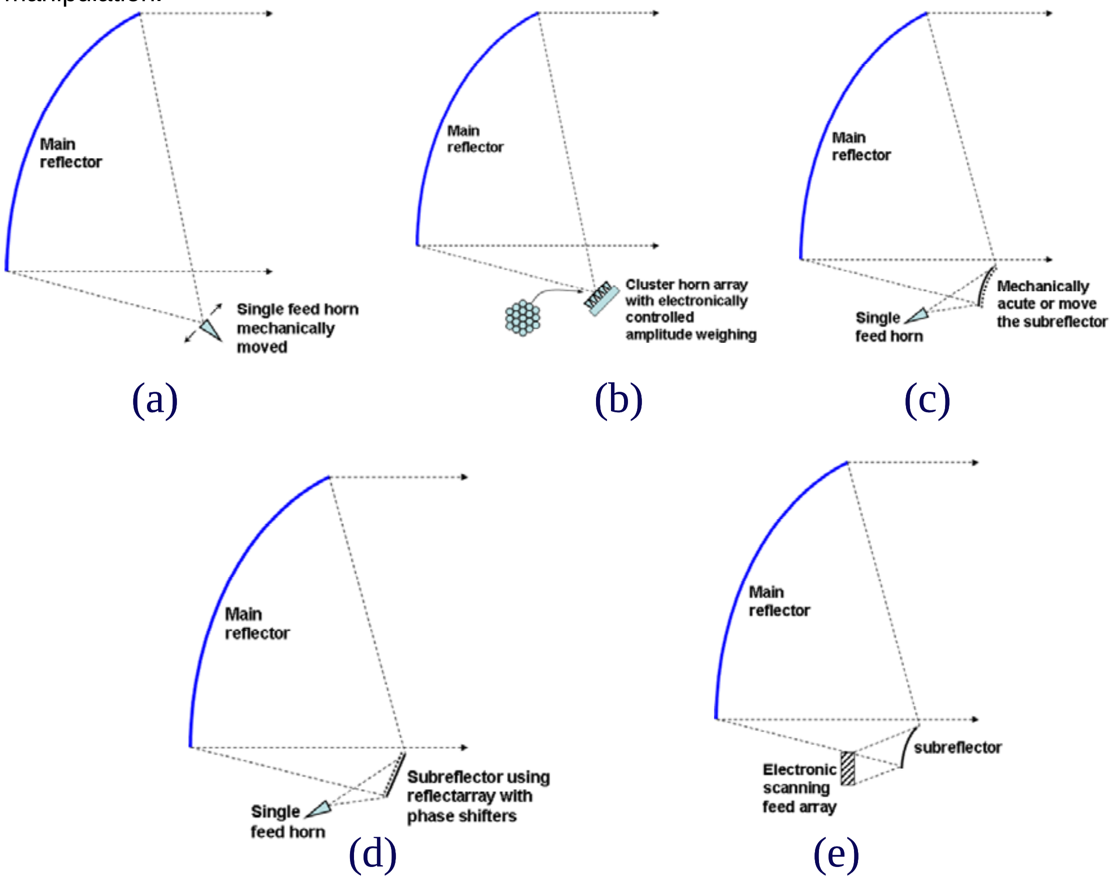


**Figure 2: Fine beam feeds: (a) Moveable feed (b) Cluster horn feed array (c) Moveable/deformable subreflector (d) Reflectarray with subreflector (e) Subreflector with electronically scanned PAA**

The most obvious method for scanning the main beam of a reflector antenna is to move a single feed horn laterally away from the focal point as shown in Figure 2(a). For a 12-m offset fed reflector with 6-m focal length, feed movement of approximately 9 mm scans the beam by one beamwidth. This system requires a mechanical servo mechanism and a moveable RF connection to move the feed in two dimensions. The flexible RF connection could be implemented with rotary joints, but since the actuation distance is very small, a simple flex waveguide may be adequate if it is shown to have sufficient reliability. Power-handling limitations and reliability issues must be addressed.

The electrical analog of the preceding concept is a cluster horn feed system as illustrated in Figure 2(b) [6]. Horns may be densely packed in one ring (7 elements), two rings (19 elements), 3 rings (37 elements), etc. Adding rings increases the maximum beam scan. A key advantage of this concept is that TWT power amplifiers can be used to drive each horn, which enables a very efficient high-power transmitter capability. There are two ways to implement this concept. One approach is to change the amplitude distribution of the array elements so that it appears that the center of the array has moved away from the focal point, thereby achieving beam scan for the main reflector. The other approach is to use a switching array, in which only a portion of the array is activated and hence allows the center of the activated array to move around the focal point. Many beam positions are needed to obtain the required fine beam-scan resolution. To accomplish this, the first approach requires large amplitude variations for each array element, which is difficult to realize without loss of efficiency. The second approach requires a very complicated switching matrix and beamformer. Consequently, both approaches are very complex and difficult to implement.

The concept depicted in Figure 2(c) depends upon mechanical movement or physical deformation of the subreflector to adjust the electrical phase front of the incident waves for beam scanning. In the latter case, the subreflector's surface, a thin membrane, is locally moved by a set of linear actuators for phase adjustment. Depending on the size of the subreflector, the number of actuators needed is in the range of 20–50. The advantage of this system is its relative simplicity and technology maturity. Also, this beam steering system does not compromise high-power handling capability. It may, however, suffer from relatively lower reliability because all actuators are connected to a single thin membrane; the failure of one actuator will impact its neighbors' performance.

The concept shown in Figure 2(d) is the electronic analog of the mechanically-oriented solution shown in Figure 2(c) [7,8,9]. This solution uses a dual-reflector system with a single feed horn and a single high-power amplifier. The subreflector is a flat active reflectarray with all of its elements equipped with electronically controlled phase shifters. By changing the phases of the reflectarray elements, the virtual center of the feed can be moved and thus steer the main beam. The phase shifter must have low RF insertion loss (< 1 dB); a MEMS switch or ferrite type may fulfill the requirements. The number of elements in the reflectarray would be 100–200. The advantage of this system is that no expensive Transmit/Receive (T/R) amplifier modules are required nore are complicated beamformer (power divider) networks needed. However, the system still requires a circuit manifold to distribute DC power and control signals, controller chips (e.g. PIC controller), phase shifter switch driver circuits, and a beam steering computer. So, while simpler than a full active electronic scanned array, the passive reflectarray subreflector is still a complex device.

The concept shown in Figure 2 (e) uses a Cassegrain dual-reflector system with a subreflector and an electronic scanned PAA feed. The feed array is located very close to, and in the near-field region of, the subreflector. The beam scan of the feed array causes the virtual center of the feed to move and, thus, cause the main beam to steer. The required number of array elements range from 100 to 1600 depending upon scan range, transmit power, focal length and other factors. A larger number of elements in the array yields improved scanned beam performance but increases cost. Currently, this is viewed as a very high cost option due to hardware complexity. However, cost should be properly weighed against the full cost of the combined feed, transmit and receive system it replaces.

The most promising technology for the electronically scanned PAA incorporates Monolithic Microwave Integrated Circuits (MMIC). In such a system, it would make most sense for each array element to consist of a T/R module that includes a power amplifier, low noise receiver, phase shifter, passive components, and digital control circuits to command the desired phase and amplitude of the RF signal. A key design challenge is to maintain a high degree of isolation between transmit and receive channels to support full-duplex operation. The Solid State Power Amplifier (SSPA) needed to generate high power is key. Higher power SSPAs offer the antenna designer more options for array architectures that meet the output power requirement. High efficiency is needed to minimize DC power draw and minimize thermal design problems.

With any of these feed-manipulation pointing techniques, the amount of beam scan that is theoretically possible increases with the ratio of the antenna focal length to the antenna diameter or the "F/D ratio". In this paper, the number of beamwidths that the reflector can scan without appreciable loss is referred to as the Fine Pointing Capture Ratio (FPCR.)

The FPCR defines the extent to which the actuation system can operate effectively — if the beam is scanned beyond that dictated by the FPCR, then scan loss is excessive and the link could fall below margin during operation. The FPCR therefore defines a cone in which the system can operate. This can be interpreted as a relaxed spacecraft attitude holding requirement. Spacecraft attitude holding requirements derived from assumed FPCR of 0 beamwidths (no fine-beam pointing, i.e. spacecraft-only pointing), 3 beamwidths and 7 beamwidths as well as several different antenna apertures are provided in Table 2 for 37.5 GHz. These values are derived to achieve a pointing loss less than 1 dB.

Note that the larger FPCR values correspond to less stringent attitude holding requirements on the spacecraft.

**Table 2: Spacecraft pointing requirements as a function of FPCR and antenna aperture.**

| Frequency (GHz) | 37.5 | Point requirement (mrad) | | |
|---|---|---|---|---|
| Taper factor | 1.1345 | L point = 1 dB, FPCR = ... (BW) | | |
| Aperture (m) | HPBW (mrad) | 0 | 3 | 7 |
| 2.5 | 3.63 | 1.05 | 11.94 | 26.46 |
| 10 | 0.91 | 0.26 | 2.98 | 6.62 |
| 15 | 0.61 | 0.17 | 1.99 | 4.41 |
| 20 | 0.45 | 0.13 | 1.49 | 3.31 |
| 25 | 0.36 | 0.10 | 1.19 | 2.65 |

## 3. Pointing strategy considerations

A system that uses only the spacecraft's ADCS system as a basis for sensing attitude does not require an uplink for operation. However, the use of RF sensing may be required if the spacecraft attitude knowledge or holding capability is not sufficient to hold pointing levels to acceptable levels. The use of a closed loop system is especially applicable if the uplink frequency is near the downlink frequency. In such cases, effects such as thermal beam wander or other phenomena associated with reflector deformation can be compensated. The added complexity of employing an uplink must be discounted as a forward channel is likely to be needed for the purposes of spacecraft command and control. The use of a closed-loop system is especially indicated if a PAA is preferred for transmit and the addition of a receive function to the element electronic modules is practical. For the Mars case, and an aperture on the order of 10-m, the "point ahead" problem is insignificant.

Articulation of the antenna relative to the spacecraft orientation is the standard method for pointing a communications antenna. This technique is applicable for both body-fixed configurations as well as configurations that employ a gimbal for achieving independence between spacecraft pointing and pointing of the high-rate antenna. Such an approach provides for simplification of the antenna feed system. However, disturbance torques and the large moment associated with the large aperture may make maintaining accurate pointing difficult, especially in the lower altitude regimes of Mars [1]. This may become a driver for mass and power of the attitude actuation system. While a fine-pointing antenna avoids issues associated with maintaining control authority over a spacecraft with a large reflector, it requires a more complex feed.

Note that while some combinations of articulation and attitude sensing are viable, many combinations have clear appeal. As already noted, the use of an electronically scanned PAA for transmit (in combination with a subreflector) would be well suited to be combined with an electronically scanned receive mode PAA, assuming similar transmit and receive frequencies. Further note that, while it may seem natural to combine closed-loop pointing with fine pointing, it is not necessary. For example, the Thuraya satellite uses ground beacons for sensing but uses the spacecraft ADCS system to point its transmit beams [10].

## 4. Summary

High rate telemetry from Mars requires an extremely large EIRP at Ka-band. In order to conserve on-board power, extremely large apertures are considered as part of the overall system trade. Apertures on the order of 1000 wavelengths, at Ka-band, result in antenna beamwidths that approach the attitude knowledge and control capability of modern spacecraft, thereby increasing pointing losses to unacceptable levels.

The use of closed-loop systems for attitude sensing and fine-pointing systems for transmit-beam steering present an attractive option for overcoming limitations in spacecraft ADCS capability. Detailed trade studies that provide estimates of mass, power and cost are still required to reveal the most efficient system architecture.

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