NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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SYSTEMS ANALYSIS OFFICE - TECHNICAL BRIEF

SUBJECT: Infrared Acquisition and Tracking System - Preliminary Mission System Specifications.

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ABSTRACT: The preliminary system specifications from a mission point of view are herein set forth for an Infrared Acquisition and Tracking System (IRATS) to be used on-board the Apollo/Range Instrumented Aircraft for monitoring the re-entry of the Apollo Command Module (C/M).

TEXT: I. Introduction:

The concept of IR-tracking was investigated and it was found to be desirable to use it for acquiring the re-entering spacecraft and providing angular pointing data of the spacecraft relative to the aircraft (see reference 1). The angular pointing data would be useful for:

1. Pointing and slaving the aircraft's Unified S-Band communication antenna.

2. Rough trajectory calculations in real time to assist in a safe recovery of the spacecraft and more importantly its crew. (See figures 11, 12 and 13 of reference 1.)

3. Providing useful data for post flight analyses.

The Infrared Acquisition and Tracking System (IRATS) must be capable of monitoring both a nominal as well as an emergency re-entry [re-entry refers to the initial re-entry into the earth's atmosphere as well as any subsequent re-entry resulting from a skip-out after the initial re-entry (see figures 1, 2, 3 and 5 of reference 2)]. Furthermore it appears likely that the heading of the Apollo/Range Instrumented Aircraft would not always be advantageously pointed to facilitate acquisition of the re-entering spacecraft. Therefore, one of the IRATS requirements is that it shall be capable of scanning the hemisphere in order to ensure acquisition of the re-entering spacecraft.

The purpose of this paper is to present the major characteristics that the IRATS should have in order to accomplish its tasks and facilitate a successful re-entry. The characteristics which follow are from a mission point of view, rather than a detailed specification. Any detailed specification, in particular for procurement and/or design purposes, should be predicated on the following characteristics.

II. Infrared Acquisition and Tracking System Characteristics.

In summary, the (IRATS) system should have the following major characteristics and/or capabilities: (See also paragraph II of reference 1.)

1. Hemispherical coverage (i.e., a 2π steradian scan capability) with a 99.0% probability (assuming clear sky conditions) of acquiring the re-entering spacecraft during the time when the spacecraft is approaching the IRATS at:

    (a) An elevation angle $\varepsilon = 1^\circ$ to 2°, which corresponds to a slant range $r \cong 540$ n. mi. and a maximum allowable acquisition time of ~ 5 sec.

    (b) An elevation angle $\varepsilon = 5^\circ$ to 6°, which corresponds to a slant range $r \cong 350$ n. mi. and a maximum allowable acquisition time of $\sim 2\frac{1}{2}$ sec.

2. In designing the IRATS to meet the above requirements, the designer may assume:

    (a) The aspect angle is such that the IRATS is at a nominal operating altitude of 35,000 ft. and viewing the leading blunt side (hot heat shield side) of the spacecraft. It is understood that when viewing the back side (which may be somewhat cooler) the maximum acquisition range capability of the IRATS might be less than specified in (1) above. (See figures 3 and 4 of reference 1.)

(b) The target may be assumed to have the following thermal characteristics for the various re-entry trajectories to be expected:

(1) The projected area of the spacecraft is approximately $12.2m^2$.

(2) Its surface temperature is approximately $1000^{o}K$ to $2000^{o}K$ at the heat shield (leading surface). These temperatures vary with range and altitude and are subject to some change with time when more detailed analyses become available.

(3) The target shall be considered to be a gray body, Lambertian radiator with an emissivity of 0.75.

3. The IRATS should be capable of discriminating the "real" target from all false targets and locking onto the "real" target with a 99.0% probability whenever its line-of-sight to the spacecraft is not blocked by clouds or other objects.

4. These false targets include, but are not limited to:

(a) Clouds which are illuminated by the sun.

(b) The sun itself (the IRATS must be capable of scanning through the sun).

(c) Other luminous objects or bodies.

(d) The Apollo Service Module, a "false target", is expected to be re-entering the atmosphere behind the "real target", the Apollo Command Module (C/M). It is expected that this "false target" (Service Module) may be tumbling when re-entering and hence could be re-entering ballistically, while the "real target" has a lifting body type re-entry trajectory. This factor may be used in discriminating the "real target".

5. An operator, assisted by a visual display such as a PPI scope, should be considered as part of the discrimination loop for reasons of reliability, maintainability, and simplicity. However, the task

of discrimination should not be left solely to the operator. Other discriminating techniques should be employed, particularly in the associated circuitry.

6. After acquisition and locking onto the real target, the IRATS should be capable of performing angular tracking with:

   (a) A maximum angular tracking rate capability of 20 degrees per second for overhead passes of the spacecraft. Although this slew rate is in general conservative, it was chosen partly because it is compatible with the aircraft antenna's specified slew rate.

   (b) Azimuth and elevation angle outputs to within an accuracy of $\pm$ 5 mrad (1σ) total angular error; this total angular error includes all bias and random errors in both the IRATS as well as the platform used for providing the aircraft heading and the local vertical.

   (c) Azimuth and elevation angle outputs at rates of at least 10 to 20 per second. These data rates are chosen primarily because they are compatible with the earlier requirements.

   If faster data rates are needed for slaving the aircraft communication antenna, then data smoothing techniques may be employed.

7. (a) The data-including azimuth, elevation, time, aircraft latitude and longitude, and aircraft identification should be sampled and transmitted to a re-entry ship or ground station at the rate of once or twice per second. This is required in order to facilitate rough trajectory calculations on the ground.

   (b) It is desirable to know at all times the aircraft position to within about $\pm$ 3 n. mi. This requirement is predicated on preliminary analyses for the case in which the angular pointing data simultaneously from two aircraft could be used to point the ship's AN/FPQ-10 antenna for quick acquisition in the circular scan mode and subsequent skin tracking. See the appendix for more details. (See also reference 3.)

8. The IRATS should be designed such that:

(a) It can readily be mounted within a dome, behind the cockpit, and on top of the Apollo/Range Instrumented Aircraft. (See figure 5, reference 1.) These aircraft will probably be the Air Force JC-135A jet aircraft.

(b) Aerodynamic fairings associated with the IRATS should not obstruct the hemispherical coverage.

(c) It should be mounted such that the heat from the jet engines will not interfere with its performance in any way.

(d) It has the capability to operate as specified at all the environmental conditions which might be encountered while on-board the aircraft which include environmental conditions which might be encountered at:

(1) All altitudes between sea level and the maximum altitude capability of the Apollo/Range Instrumented Aircraft which is about 45,000 ft. The nominal operating altitude may be considered to be 35,000 ft.

(2) All points on the earth between latitudes of 40^{o} South and 40^{o} North, primarily because the nominal re-entry corridors are between these latitudes; also, the stations from which the Apollo Aircraft would be deployed presumably are located between these latitudes. (See figures 6 and 7 of reference 2.)

(3) Take-off, landing, and flight operations for all aircraft speeds. The nominal cruising air speed of a JC-135A is $\sim$450 knots.

(e) Its power and space requirements are compatible with the JC-135A. The available power is 115v, 400 cps, and about 2 kw.

III. Acknowledgements:

This writer wishes to acknowledge the assistance and helpful comments obtained from Drs. F. O. Vonbun, R. Lehnert, and Messrs. H. L. Richard, D. Premo, L. Shelton, and N. K. Shaw.

IV. References:

1. Vonbun, F. O., "Apollo Re-entry Infrared Support," GSFC Report X-513-65-4, Dec. 5, 1964.

2. Vonbun, F. O., "Re-entry Tracking for Apollo," GSFC Report X-513-64-85, March 6, 1964.

3. Kalil, F., "Navigation Accuracy for Infrared Equipped Apollo Aircraft for Re-entry Tracking," GSFC Report X-513-65-11, Jan. 5, 1965.

4. Moore, J. R., "Recommendations for Improved Acquisition Systems for Aircraft," GSFC Report X-513-65-12, December 30, 1964.

5. Plotkin, H. H., "Infrared Re-entry Tracking," GSFC Report X-524-62-136, Aug. 10, 1962.

Appendix I

As pointed out earlier in the text, the concept of I-R tracking and corresponding requirements from a mission point of view were analyzed with regards to using on board the Apollo/Range instrumented aircraft an infrared acquisition and tracking system (IRATS). The IRATS would be capable of both acquiring the re-entry spacecraft and providing angular data of the spacecraft relative to the aircraft.

In the following paragraphs, the method(s) of utilizing the angular pointing data and the corresponding problems are briefly discussed from the viewpoint of what the IRATS requirements should be. Some preliminary analyses are included whenever applicable. (See also reference 1.)

I. Angular Pointing Data From One Aircraft.

The angular pointing data from one aircraft could be used as follows:

A. Pointing and slaving that aircraft's communication antenna. This in itself poses some interesting problems. Mr. J. R. Moore (reference 4) has made some recommendations regarding the configuration and location of the Unified S-Band System (USBS) antenna, which is not presently specified but is to be part of the Program Definition Phase contract. The same antenna will be used for the VHF communication link. The USBS is the primary communication link to the Command Module (C/M). It is the writers understanding that the VHF link is the primary telemetering link to the SIVB during the injection phase of a lunar mission and that this VHF would also serve as a back-up for the USBS link to the C/M. The angles through which the USBS antenna could be pointed relative to the aircraft frame will be part of the specifications for the Program Definition Phase contract.

As pointed out before, the aircraft heading might not always be advantageously pointed for acquiring the re-entry aircraft. Even in the case of a nominal re-entry, the aircraft equipped with an IRATS would probably fly in a pre-specified flight pattern and in a pre-selected area where the cloud cover would not be expected to present an unduly severe handicap. This is one of the reasons for requiring that the IRATS have the hemispherical scan capability.

Should the aircraft be headed in a disadvantageous direction when the IRATS acquires the spacecraft, it is conceivable that the communication antenna with its limited angular mobility could not point at the spacecraft without the aircraft doing some maneuvering. Hence, the aircraft's maneuverability needs to be considered. The aircraft maneuvering time may be long relative to the time the spacecraft is in the field of view of the IRATS, and it may not always be possible to get the communication antenna pointed at the spacecraft.

The angular pointing accuracies required from the IRATS in order to point the aircraft communication antenna are not at all stringent because of the relatively broad antenna beamwidth ($\sim 5^{\circ}$ at S-Band) which is expected. Therefore, the pointing accuracy requirements are based on more stringent requirements to be discussed below and which are well within the state-of-the-art.

B. Rough trajectory analyses in real time to facilitate an effective recovery of the spacecraft and more importantly its crew.

This facet of the problem is presently being investigated and is reported in reference 1. Hence, the following discussion will be very brief.

Any computations or predictions of the spacecraft trajectory based on angular measurements from one aircraft equipped with an IRATS will be very rough, primarily because:

1. The number of independent measurements obtainable from the IRATS with reasonable accuracy are basically the azimuth and elevation angles of the slant range vector from the aircraft to the spacecraft.

2. The various parameters entering into the equations of motion of a lifting body type of spacecraft whose angle of attack, roll, pitch, yaw, and altitude are not known. This would be true particularly during communication black-out when the spacecraft cannot communicate this information to the ground. The altitude is mentioned because it is needed to determine the atmospheric density for determining the drag and lift forces on the spacecraft.

It should be pointed out that the magnitude of the slant range might be estimated from the target signal strength in the IRATS by monitoring the signal voltage at the decision making point in the IRATS circuitry or by allowing an operator to estimate the target intensity on a visual display screen. Monitoring the signal voltage would be preferable since this data can readily be recorded on a strip chart recorder, for example, and telemetered to the ground station or re-entry ship where the necessary computations can readily be made.

The above range estimate may be computed (see reference 5) by applying: (a) the Planck's law of radiation to compute the irradiance of the target over the wavelength region of interest ($\sim 3.4\,\mu$ to $\sim 5.3\,\mu$ for an Indium Antinomide detector, a type of detector with the fast response time $\sim 10^{-6}$ sec which is needed to give the hemispherical coverage and acquisition probabilities within the specified times). Here is where the targets temperature and thermal characteristics need to be known. (b) The inverse square law which states that the intensity of radiation received by the IRATS is inversely proportioned to the square of the slant range from the target to the detector. In addition the detector sensitivity (or noise equivalent flux density) and atmospheric attenuation must be taken into account. The detector sensitivity is assumed to include such factors as optical efficiency, signal conversion efficiency, aperture diameter, scanning rate, number of detectors, etc.

It may be expected that the estimated range obtained in the above manner could be wrong by a factor of about three primarily because of uncertainties in the spacecraft's temperature profile and its physical orientation namely the aspect angle relative to the IRATS.

II. Angular Pointing Data From Two Aircraft.

The spacecraft position could be monitored by triangulating the angular pointing data obtained from more than one aircraft simultaneously. Although this mode of operation is not presently recommended because of the operational complexities, it should be mentioned. A knowledge of the spacecraft's position, particularly during blackout, could be used for:

1. Pointing the re-entry ship's tracking and communication antennae for both skin tracking during blackout and immediate radio contact with the spacecraft at the termination of blackout.

2. Providing useful real-time trajectory data which would be more accurate than the rough trajectory calculations based on angular tracking data from only one aircraft, assuming the aircraft positions are adequately known.

3. Providing useful data for post flight analysis.

The accuracy of the trajectory calculations or spacecraft position data discussed above are dependent on how well the aircraft positions are known. For example, it could be assumed that the spacecraft position error should be comparable to the spacecraft's on-board navigation capabilities and/or within the re-entry ship tracking system's circular scan beamwidth to ensure quick acquisition and skin tracking during the ion plasma blackout. Based on these assumptions, a parametric study was made in order to ascertain the trade-offs between the angular pointing accuracies of the IRATS and the aircraft navigation requirements.

Shown in Figure 1 is the tracking geometry which was used in the analysis.

From Figure 1, it can be seen that

$$(\sigma_{pos})_{S/C,\ I-R} = \pm \tfrac{1}{2}\sqrt{D_1^2 + D_2^2 + D_3^2} \qquad 1)$$

= spacecraft position error using I-R angular tracking from two aircraft.

In order to simplify the mathematics, and to facilitate a parametric analysis, the following assumptions were used:

1. $R_1 > R_2$ so that $D_1 > D_2$, and replace D_2 by D_1 to be conservative.

2. The angular errors from the two aircraft are equal, i.e., $\delta\alpha_1 = \delta\alpha_2$ and $\delta\epsilon_1 = \delta\epsilon_2$.

3. The azimuth and elevation angular errors are equal, i.e., $\delta\alpha = \delta\epsilon$.

4. The aircraft latitude and longitude position errors are all equal so that $\delta p_1 = \delta p_2$.

5. The aircraft use a radioaltimeter, and the altitude errors are negligible compared to the other errors involved.

6. The correlation coefficient $\rho_{\alpha p} = \rho_{\epsilon p}$.

Based on these simplifying and probably conservative assumptions, it can be shown that equation 1 becomes

$$(\sigma_{pos})_{S/C,\ I-R} \cong \pm \left[3R_1 \delta\alpha_1 + 2(\delta p_1)^2 + (\delta p_1 \sin\epsilon_1)^2 + 2\rho_{\alpha p} R_1 \delta\alpha_1 \delta p_1 (2 + \sin\epsilon_1) \right]^{1/2} \qquad 2)$$

where the various quantities are adequately defined in figure 1.

If it is further assumed that the spacecraft position error must be equal to or less than the circular scan beamwidth of the ship's AN/FPQ-10 tracker, then three sigma (3σ) values must be used for the various errors in equation 2. Based on this, a parametric study was made and the results are shown in Figures 2, 3, 4, and 5. It should be emphasized that the errors shown in these figures are three sigma values, and that the angular errors are the total errors including all bias and random errors of both the IRATS and the platform which provides the aircraft heading and the local vertical.

Shown in Figures 2 and 3 are the results for a correlation coefficient of zero, since it is not presently known just what the value of this correlation coefficient might be. However, the IRATS angular pointing errors might be highly correlated to the aircraft position errors particularly when the same inertial platform is used for navigation as well as providing the local vertical and aircraft heading. Therefore, the case shown in

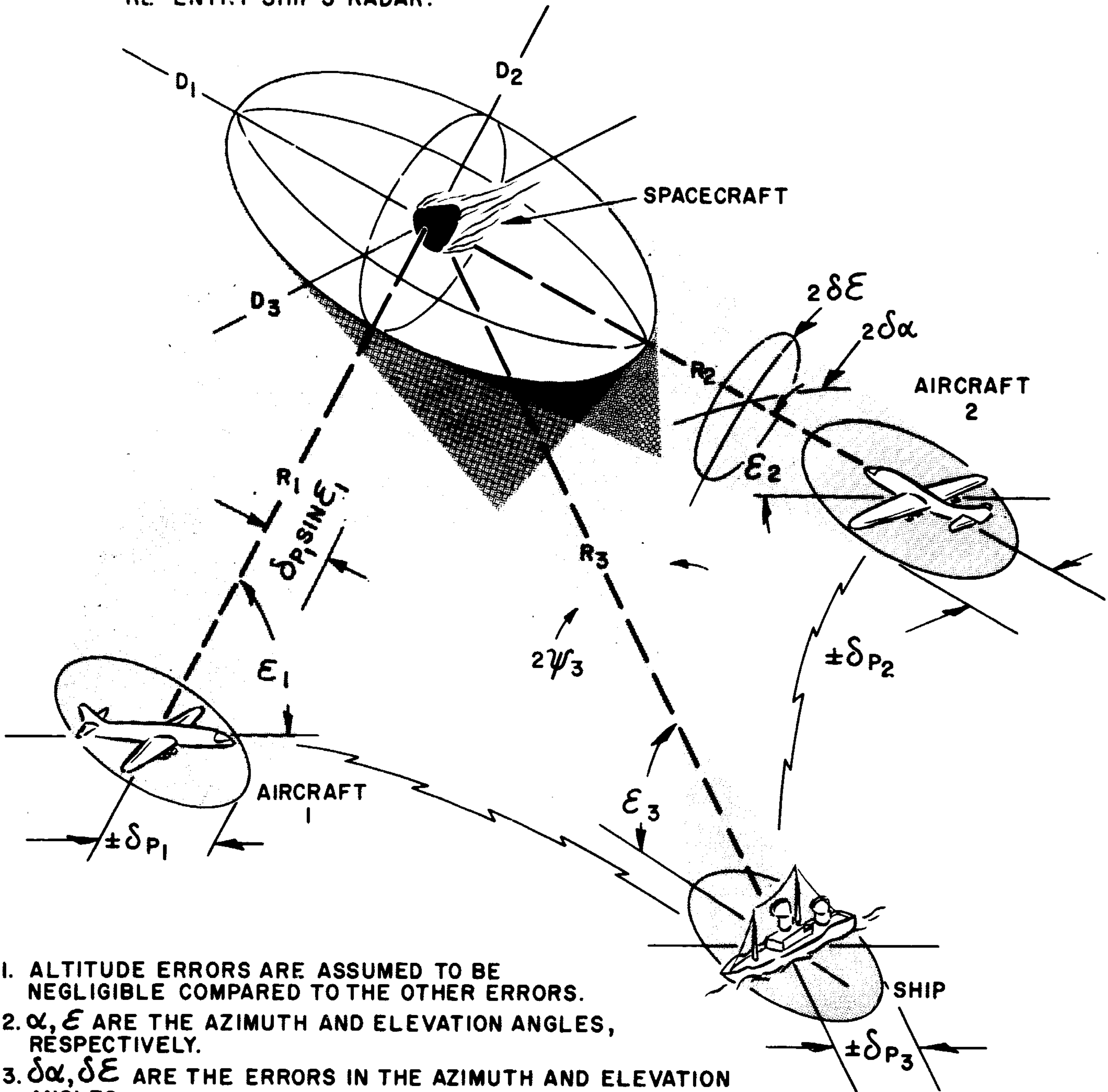
Figures 4 and 5 are for the extremely pessimistic case of a correlation coefficient of + 1. It is conceivable that this correlation coefficient might even be negative. Hence, pending further analyses to justify otherwise, it is recommended at this time that the correlation coefficient be taken to be zero.

From these figures, it appears likely that a judicious choice for the <u>one sigma</u> allowable error in the position of each of the two aircraft is $\pm$ 2 n.mi. on each axis in order to effectively point the AN/FPQ-10 on board the re-entry ship. It should be pointed out that relatively inexpensive inertial platforms are available which provide the aircraft heading and local vertical - each to the required accuracy of about $\pm$ 4 mrad which would allow the IRATS angular errors to be about $\pm$ 4 mrad so that the total angular error is $\pm\sqrt{4^2 + 4^2}$ or about $\pm$ 5.7 mrad. However, an inertial navigation system which must also provide the aircraft position to an accuracy of $\pm$ 3 n.mi. over extended periods of time could be quite expensive. Therefore, it is recommended that the use of other navigation systems such as the following be investigated. For example, such systems could be used for periodic position fixes and updating a relatively inexpensive inertial navigator.

1. LORAN-C which could provide the aircraft position to within about $\pm$ 1500 ft (2σ) in daytime use, although adequate LORAN-C coverage is not presently available in the Pacific Ocean area. It is not presently known what the plans are for adding LORAN-C stations in this area.

2. The U. S. Navy's OMEGA system which is scheduled to be operational by 1968 and which will provide world-wide coverage to within LORAN-C type accuracies. The Navy Research Laboratory is presently developing an OMEGA receiver for use on aircraft. For further information, Lieutenant Commander Cecil C. Stout, Code 362A, BuShips, Room 2512 (Phone: IDS 11-64125) may be contacted.

FIGURE 1. TOP VIEW OF TRACKING GEOMETRY USING TWO AIRCRAFT EQUIPPED WITH IRATS FOR DETERMINING SPACECRAFT POSITION AND/OR SLAVING THE RE-ENTRY SHIP'S RADAR.



1. ALTITUDE ERRORS ARE ASSUMED TO BE NEGLIGIBLE COMPARED TO THE OTHER ERRORS.
2. α, ε ARE THE AZIMUTH AND ELEVATION ANGLES, RESPECTIVELY.
3. $\delta\alpha, \delta\varepsilon$ ARE THE ERRORS IN THE AZIMUTH AND ELEVATION ANGLES.
4. δp IS THE POSITION ERROR ON EACH AXIS.
5. R IS THE SLANT RANGE VECTOR.
6. ψ IS THE SHIP TRACKER BEAM WIDTH IN A SPIRAL OR CIRCULAR SCAN MODE.
7. THE D'S ARE THE AXES OF THE SPACECRAFT ERROR VOLUME.

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JAN 1965

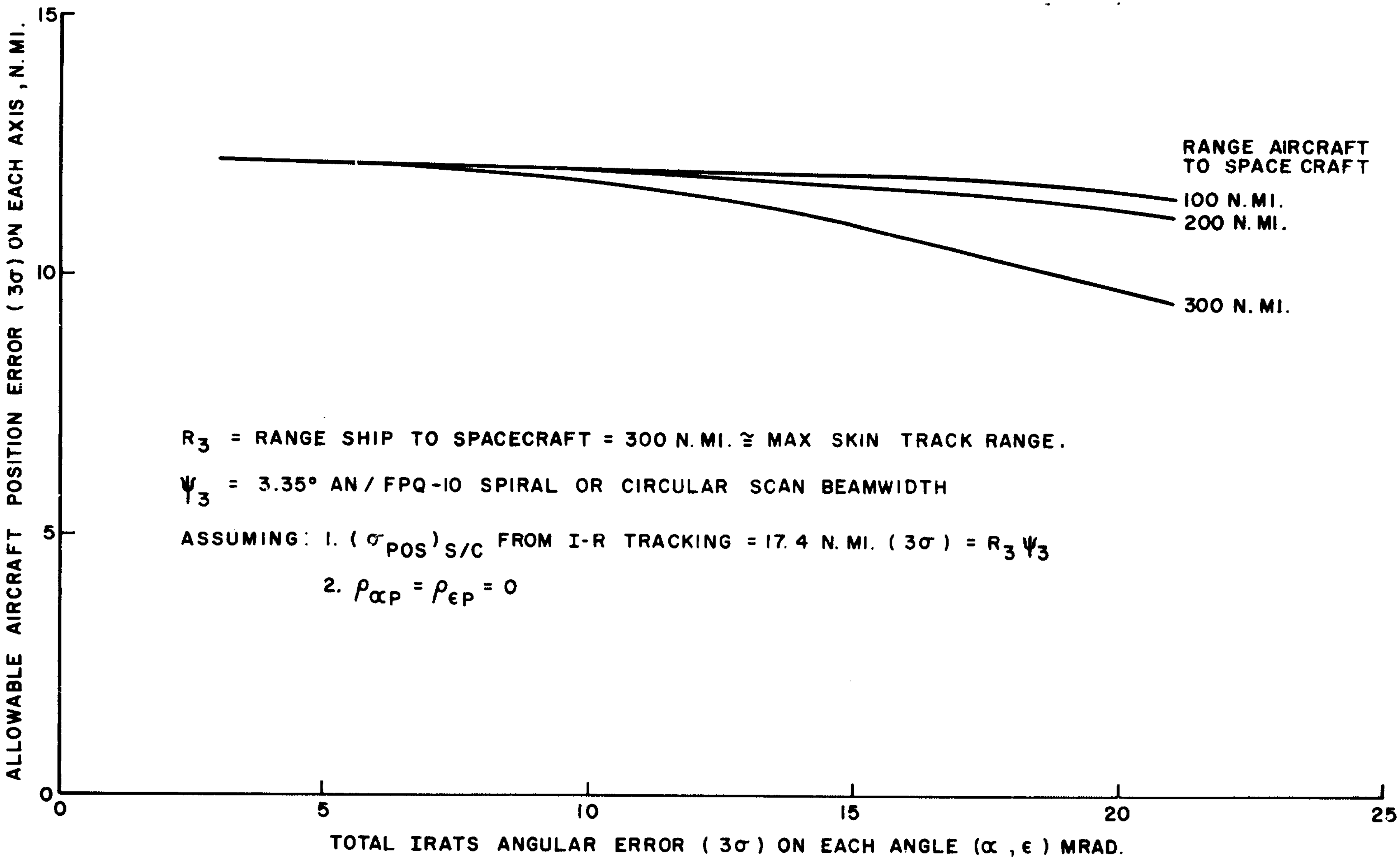

FIGURE 2. APOLLO / RANGE INSTRUMENTED AIRCRAFT NAVIGATION REQUIREMENTS AS A FUNCTION OF THE IRATS ANGULAR POINTING ERRORS.

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JAN 1965

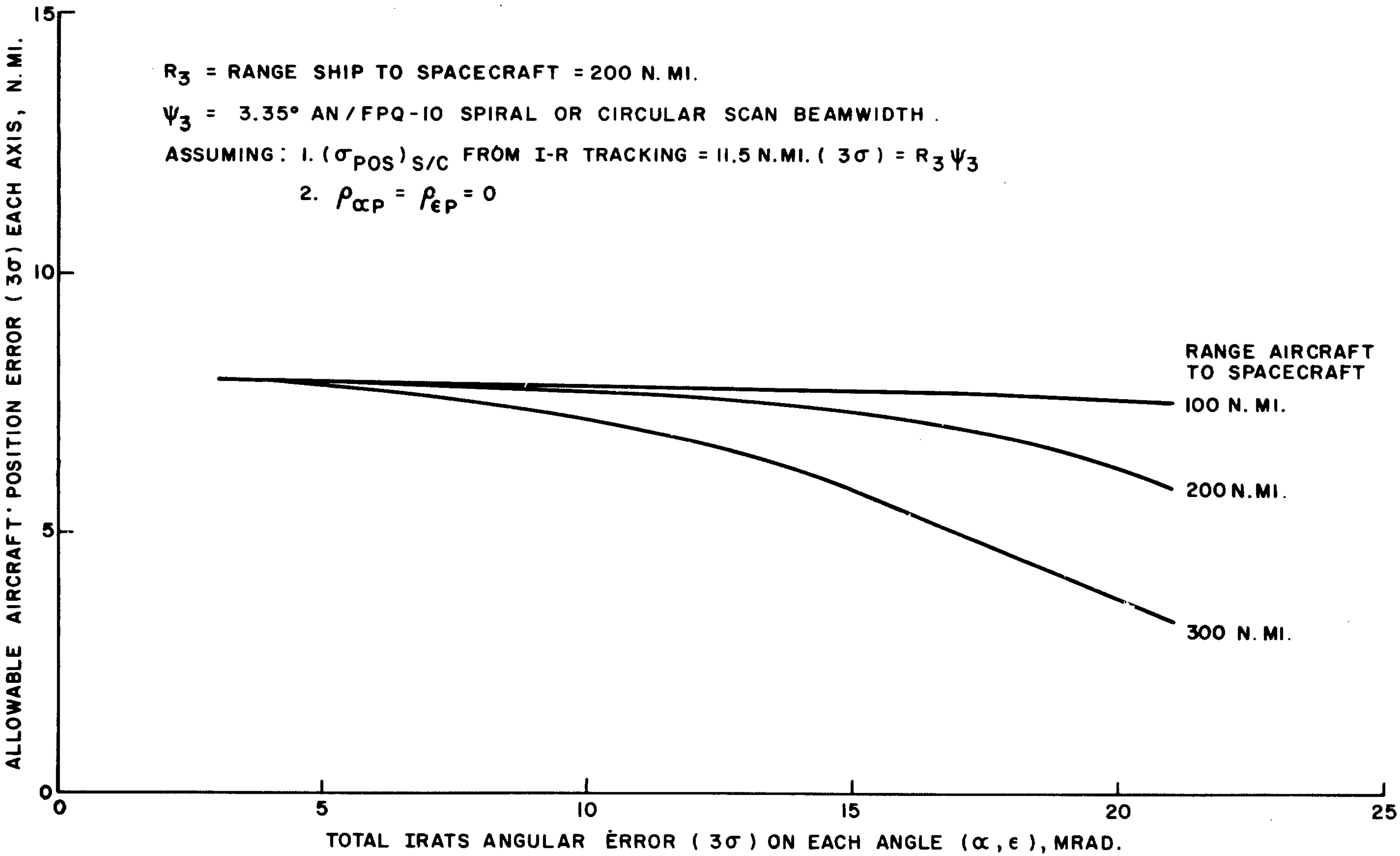

FIGURE 3. APOLLO / RANGE INSTRUMENTED AIRCRAFT NAVIGATION REQUIREMENTS AS A FUNCTION OF THE IRATS ANGULAR POINTING ERRORS

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JAN 1965

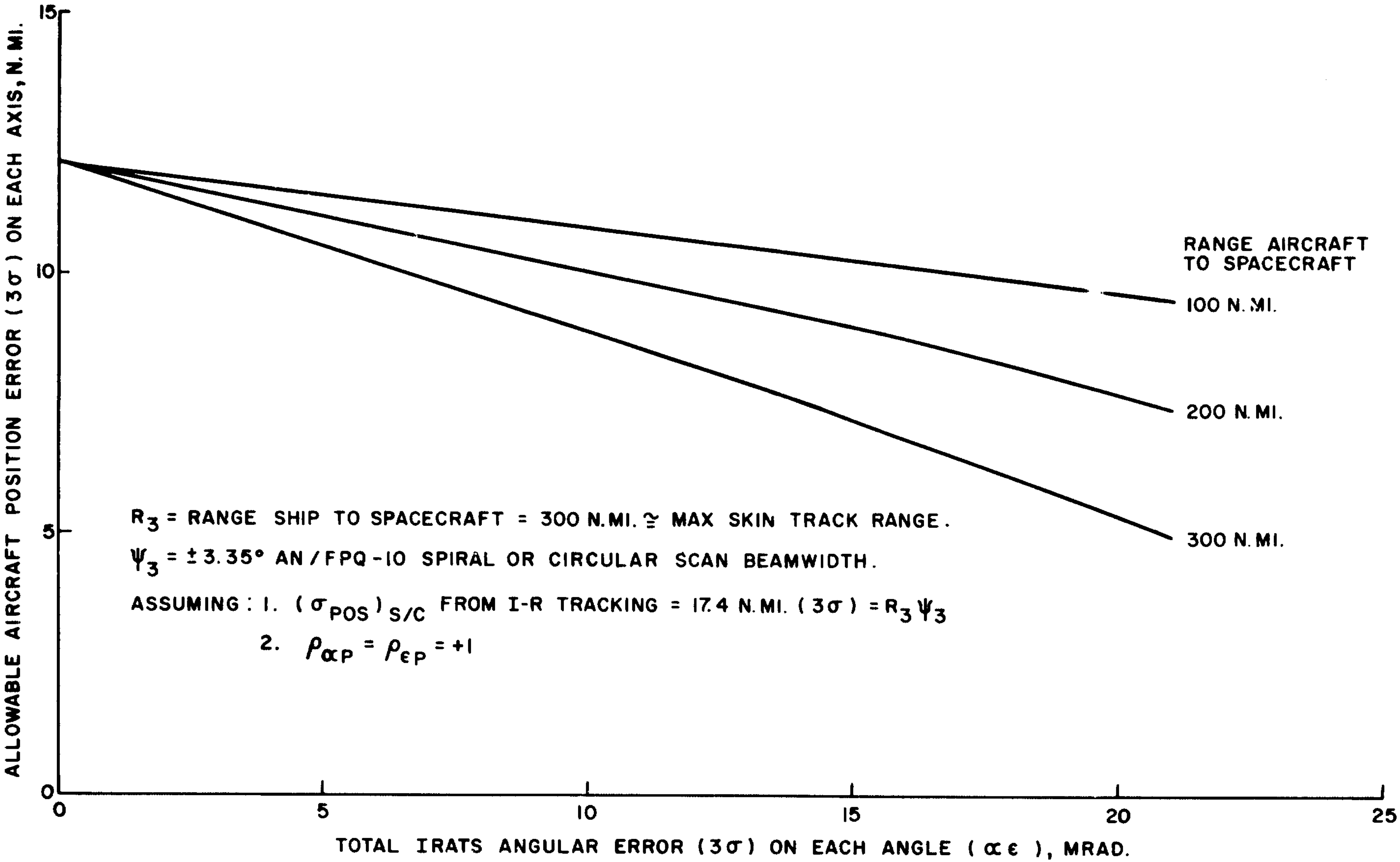

FIGURE 4. APOLLO / RANGE INSTRUMENTED AIRCRAFT NAVIGATION REQUIREMENTS AS A FUNCTION OF THE IRATS ANGULAR POINTING ERRORS.

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JAN 1965

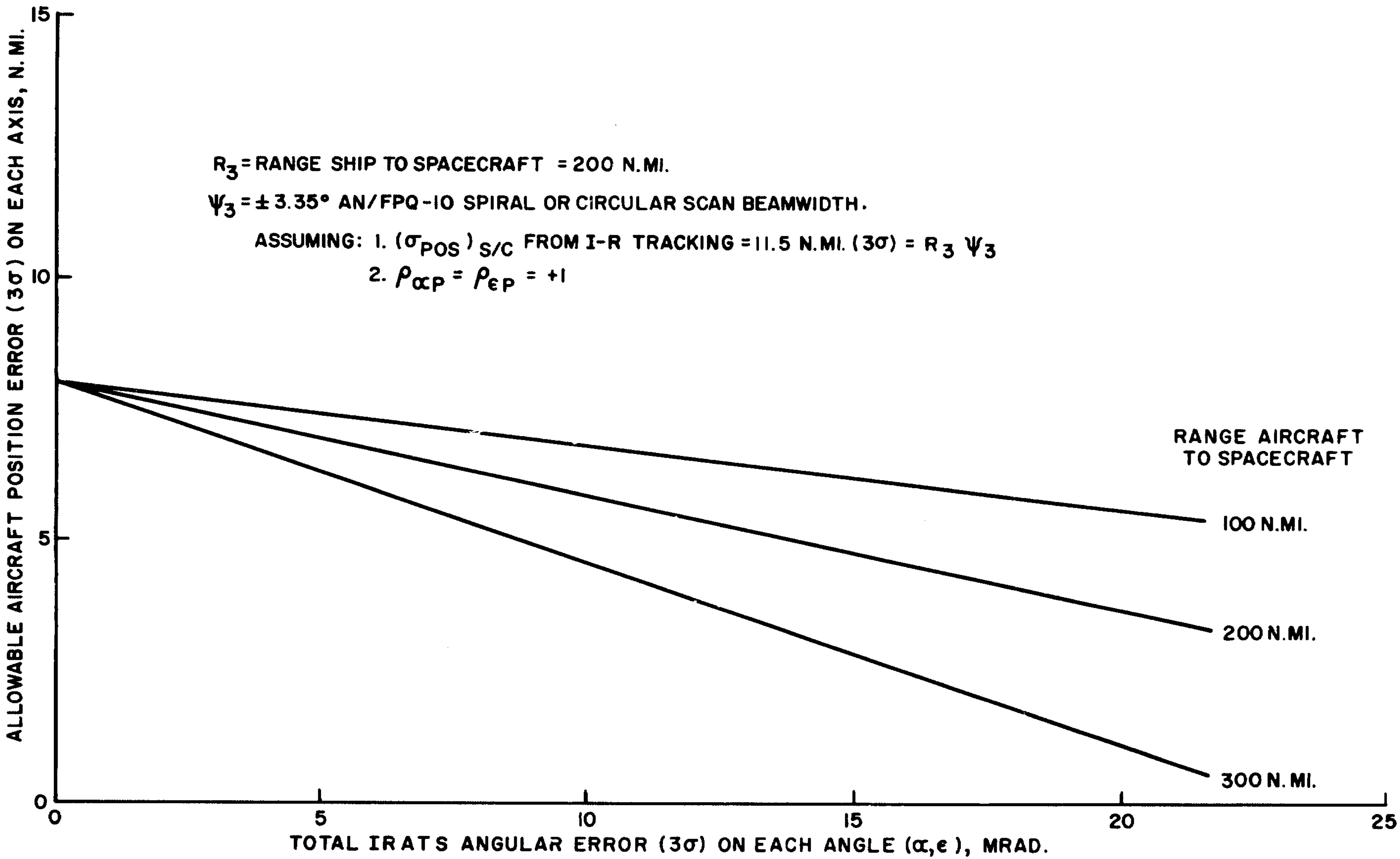

FIGURE 5. APOLLO / RANGE INSTRUMENTED AIRCRAFT NAVIGATION REQUIRMENTS AS A FUNCTION OF THE IRATS ANGULAR POINTING ERRORS.

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