Computerized Ionospheric Tomography

Arnold J. Tucker

With the transition to the Global Positioning System, Transit has been decommissioned, after having served well for the Fleet. A new system, the Navy Ionospheric Monitoring System, was established using Transit satellites. This article examines the application of the new system to the field of computerized ionospheric tomography.

(Keywords: Computerized ionospheric tomography, Dual-frequency ionospheric measurements, Ionosphere, Navy Ionospheric Monitoring System, Transit.)

INTRODUCTION

On 1 January 1997, Transit became the Navy Ionospheric Monitoring System (NIMS). Its satellites are being used as dual-frequency beacons by ground collection sites to determine the free electron profile of the ionosphere (Fig. 1). Tracking, telemetry, and commanding (TTC) functions continue to be performed at the Naval Satellite Operations Center, Point Mugu Naval Air Warfare Center, California, and at a new facility established at the Applied Research Laboratories (ARL) of The University of Texas at Austin.

The TTC stations have been redesigned and upgraded to enhance their reliability while reducing long-term operational costs. The redesign is based on the use of commercial off-the-shelf hardware and software. The new system was built around industrial-standard VXI architecture. Each station operates semi-autonomously for receiving, processing, and archiving satellite health and telemetry data.

The current Transit constellation consists of six Oscar satellites located in three planes, with two satellites per plane. Each satellite can transmit signals at 150 and 400 MHz at −80 ppm (operational) oscillator offset or −145 ppm (maintenance) oscillator offset. As the phasing of the satellite changes because of the precession of each orbit, it will transmit on either the operational or maintenance frequency.

COMPUTERIZED IONOSPHERIC TOMOGRAPHY

Background

The ionosphere is a plasma that affects the transionospheric propagation of radio signals above approximately 30 MHz, and this effect is frequency dependent. The atmospheric gases present in this region become ionized by solar radiation. The electron density of the ionosphere has a dynamic quality due to the continuous recombination of electrons and ions and the formation of new ions caused by solar radiation.

The ionosphere protects the Earth's surface from high-energy radiation, and it makes radio communication possible beyond the horizon. Specifically, radio waves of
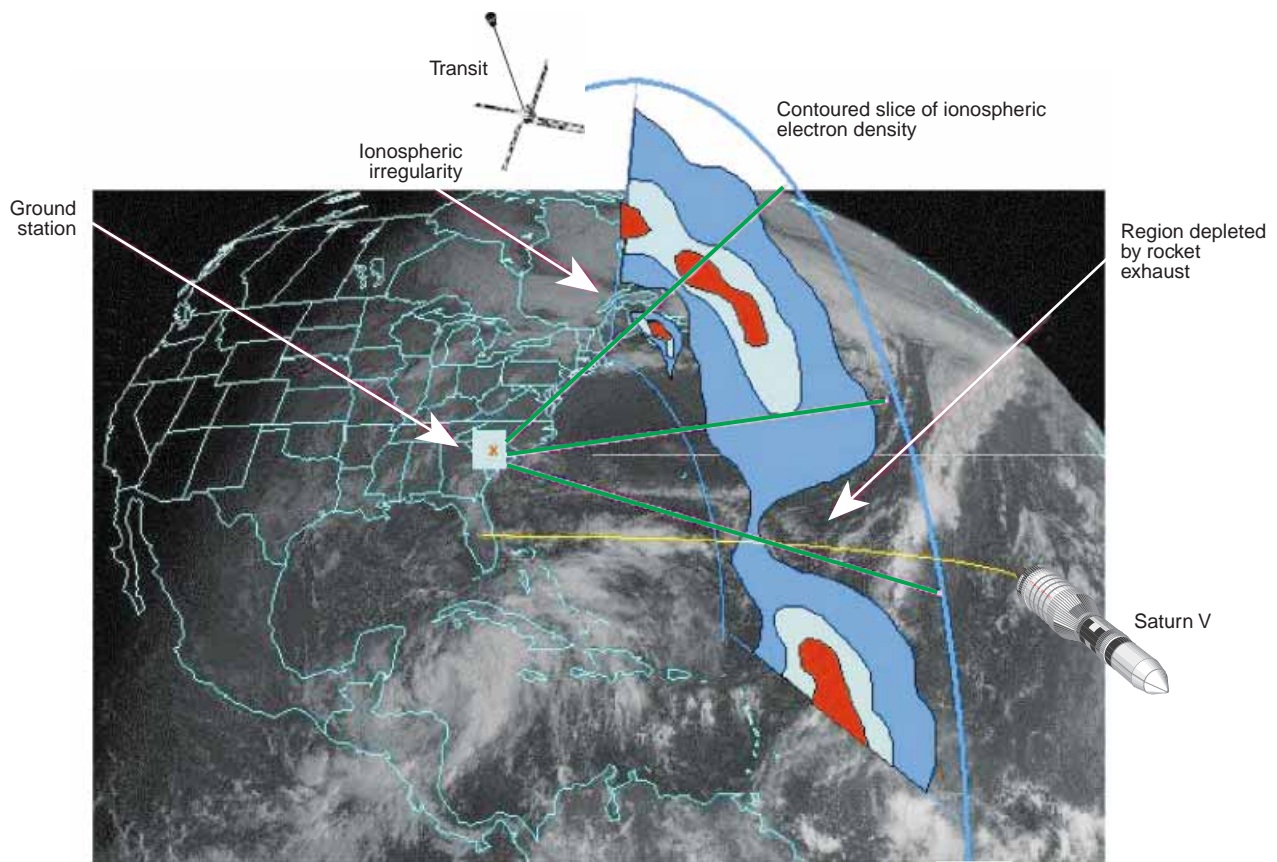
Figure 1. Transit has taken part in numerous ionospheric experiments like the ones represented here (green lines = lines of sight to satellite).

certain frequencies bounce off the ionosphere so that they return to Earth and are detected at great ranges.

The first Transit satellites transmitted signals at four frequencies: 54, 162, 216, and 324 MHz. Simultaneous measurements of all four signals provided experimental data to evaluate ionospheric effects as a function of frequency. These data were limited in duration and global location. To further observe ionospheric effects throughout a solar cycle and at selected global locations near the magnetic equator, two NASA beacon exploration satellites collected additional data in the mid-1960s. Those measurements supplied experimental data that were used to verify assumptions about ionospheric effects and characterize the magnitude of the residual ionospheric effect for the navigational and geodetic positioning error budget.

The final design of Transit was based on a two-frequency method for correcting ionospheric error; at 150 and 400 MHz, the first-order ionospheric effect dominated, and all higher-order effects were negligible.[1] These latter effects are caused by the bending of the signal path of each signal and the difference in phase velocity between each path.

The dual-frequency signals from the Transit satellite yield real-time measurements of the changes in total electron content (TEC) between the satellite and receiver. The uses to which these measurements have been applied, as depicted in Fig. 1, include

- Mapping the morphology of the ionospheric regions and understanding the daily and seasonal changes through several solar cycles at different geomagnetic sites
- Investigating the occurrences of ionospheric irregularities
- Observing ionospheric modifications (both natural and man-made)

Computerized tomography was proposed as a method of imaging the ionosphere in 1988.[2–5] In the early 1990s, this new technique began being used in experiments to provide a more complete mapping of the ionosphere. Called computerized ionospheric tomography (CIT), it applies medical tomographic methods to the study of the ionosphere. Tomographic methods were formulated by Radon in 1907 as a means of remotely mapping inaccessible regions of the body. This requires a transmitted signal to propagate through the region of interest to a receiver. The transmitter and receiver (or the region of interest) are rotated, and data are recorded. Each data sample contains information about the region from a different perspective. The region being mapped must be affected by the transmitted signal and is assumed not

to change during the measurement period. Then tomographic algorithms (e.g., computer-aided tomography scans, magnetic resonance imaging) are used to generate a map of the specific region. These techniques have been adapted into the field of ionospheric research.

Concept and Goals

The basic concept (Fig. 2) in CIT research is to use low-flying satellites (e.g., Transit) as moving transmitters and an array of ground receivers to measure TEC in the ionosphere. The resulting set of data can then be used to determine the two-dimensional number density using the following equation:

$$\text{TEC}(\beta, X_r) = \int N_e \, ds,$$

where

β = elevation angle,

X_r = location of receiver,

N_e = electron number density, and

s = arc link.

The TEC is obtained from the receiver Doppler data by estimating an unknown constant of integration. By using an array of receivers and collecting data over a large angular aperture, the number density can be reconstructed from the data.

The primary goal of CIT research is to quantify improvements in modeling the ionosphere using experimental data from rocket probes, remote satellites, ionosondes, and incoherent scatter radar. It does, however, have several features that make the reconstruction of a near–real-time two-dimensional image of the electron number density difficult. For example, as noted previously, the ionosphere is a dynamic medium. Since the transmitter is moving across the ionosphere, a static field approximation must be made or time and spatial dependence must be included in the inversion
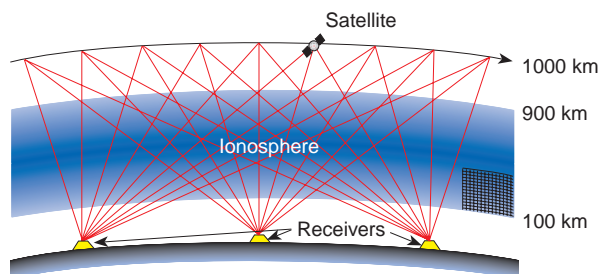
algorithm. In addition, observations are limited by the minimum elevation angle, below which strong refraction effects degrade the TEC data; the maximum rate at which data are collected; and the number and spacing of the receivers in the array. Finally, the primary interest of medical tomography is in the relative contrast of structures, whereas the CIT technique requires a knowledge of the actual number density. Data obtained under these constraints have been shown to be insensitive to certain classes of background ionospheres, particularly stratified ionospheres.[3] Thus, unless *a priori* data are included from other sources, the reconstructed number density is only accurate up to a class of background ionospheres.

Recent work in CIT has focused on understanding the limitations inherent in the data and developing optimized reconstruction algorithms.[4,6,7] A few researchers have done simulations and testing of the reconstruction methods (e.g., Ref. 3); however, a comprehensive simulation/experimental analysis of the accuracy and limitations of CIT has not been attempted. In particular, the ability of CIT reconstructions to improve radio-frequency propagation prediction has not been investigated. Since high-frequency communication makes use of ionospheric refraction to obtain beyond-line-of-sight communication, successful transmission depends on a knowledge of the relationships among critical frequency, layer height, radiation angle, path length, etc.

One example of a high-frequency application of CIT is direction finding using a single sight location (SSL), which observes elevation and azimuth angles of arrival and estimates range. Knowledge of the virtual height at the reflection location and reflection time is required. Today's systems use a vertical sounder at the receiver location and assume that the ionosphere is constant along the path.

Conceptually, the CIT technique can improve range estimates for a single location by more accurately characterizing the ionosphere. However, given the constraints of a realistic operational system, this improvement is uncertain. A real-world array of receivers will not be aligned along a straight north–south line, nor will the receivers be equally spaced. Simulations provide a design tool for determining the optimal receiver configuration for the CIT effort, enable analysis of reconstructed ionospheres for realistic geometries, quantify the overall accuracy of the reconstructions, and assess the accuracy of virtual height estimations. Results of these simulations have indicated that the reconstructions obtained from the fixed algorithm are accurate overall to about 10%, but no improvement has been achieved by increasing the number of receivers from the base configuration of nine or by varying interreceiver spacing along the array. Local variations such as Gaussian

Figure 2. Pictorial representation of the satellite-receiver geometry for computerized ionospheric tomography (data are collected over a 10- to 20-min period; receivers are spaced 1000 to 3000 km apart).

depletion regions, however, actually seem to improve the reconstructions.

Again, to fully utilize the potential improvements from the ray-trace SSL technique, an accurate characterization of the ionosphere is required. Previous methods have relied on worldwide electron density models in conjunction with updates provided by local ionosondes. But these techniques require an active transmitter and yield measurements that have limited applicability for regions not in the immediate vicinity of the local ionosonde. An alternate method of providing ionospheric measurements for an SSL is to use CIT to reconstruct the electron density in the propagation region.

CIT Experiments

The Mid-America CIT Experiment (MACE) was conducted from July through mid-December 1993. MACE had two goals: (1) to determine whether CIT could improve SSL range estimates, and (2) to determine whether CIT was sufficiently developed to be operationally applied to ionospheric measurements. Since the primary motivation for the experiment was to investigate the capabilities of CIT using currently available hardware and software, algorithms developed by other workers in the field[6,8] as well as those developed at ARL were used during the course of the experiment. MACE '93 demonstrated that a long-term campaign could be successfully conducted. It experienced little downtime, and over 6000 passes of data were collected. The success of MACE indicated the feasibility of a permanent, operational CIT network, even when older-technology receivers were used. Figure 3 is an example of a reconstructed image obtained during MACE.

Initial analysis of the MACE '93 data yielded some interesting results.

- The standard algorithms based on mathematical techniques seemed to suffer severe problems when confronted with actual data on a regular basis.
- The data often did not support any global ionospheric model.
- The global models regularly underestimated the observed maximum frequency at which an ordinary wave is reflected in the ionosphere (foF2).

To effectively deal with the real-world demands of the data, ARL developed an "engineering-based" algorithm that combines several methods presented in the literature. The algorithm responds well to anomalous as well as regular data sets, and reconstructed foF2 peaks closely match ionosonde results. A preliminary analysis of several SSL range estimations over many CIT passes has shown that the CIT technique
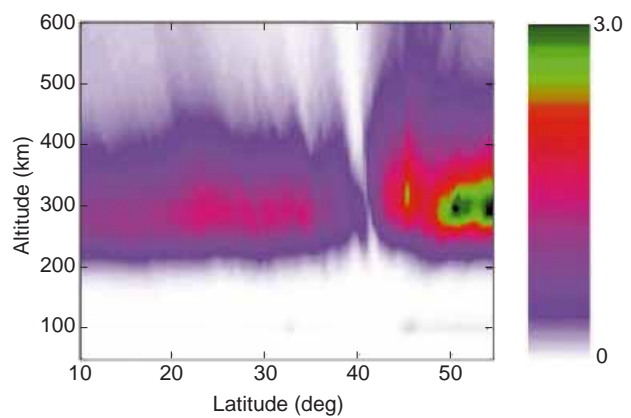

Figure 3. Reconstructed CIT ionosphere during a severe magnetic storm in November 1993 during the MACE '93 campaign. Note the clear imaging of the ionospheric trough at about 45° latitude. (Scale on right is $\times 10^{11}$ electrons/m^3.)

is a useful tool for estimating transmitter range, and is at least as accurate as SSL techniques that rely on a local ionosonde.

In another set of experiments, two chains of CIT receivers were deployed across the western United States. These chains provided simultaneous receipt of the satellite signal along two lines of longitude. A three-dimensional image of the ionosphere could be created along each longitude, as shown in Fig. 4. These images represent the ionospheric structure with a spatial resolution of 10 to 20 km. Using morphing techniques, a snapshot of the ionospheric volume can be generated, usually in increments of 1°, for any selected region (only two such images are shown in the figure for clarity). For each successive Transit pass, another volumetrical snapshot is made. To generate an ionospheric volume at other times, spatial interpolation techniques are applied. To enhance these interpolation (i.e., morphing) techniques, ionospheric measurements from the Global Positioning System are incorporated, as shown in Fig. 5. These data provide continuous TEC measurements (known as soda straws) through the ionospheric regions of interest. The measurements are combined with ionospheric tomography data to generate four-dimensional (latitude, longitude, altitude, and time) ionospheric specifications in near–real time.

Other CIT Applications

Eruptions from the Sun appearing on the Earth as disturbances in the magnetosphere, ionosphere, and atmosphere are known as magnetic storms. One area of active research is the response of the ionosphere to such storms. The midlatitude response is often delayed by several hours and can last for several days. We do
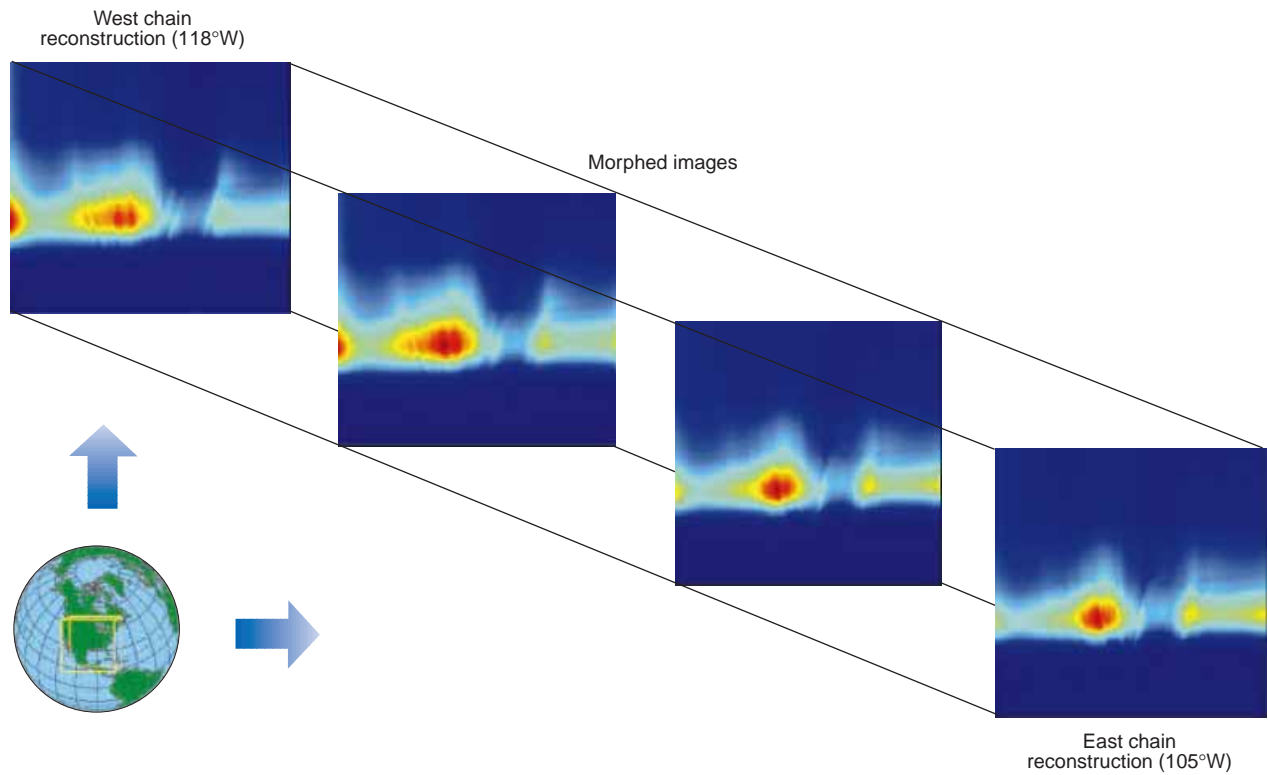
West chain
reconstruction (118°W)

Morphed images

East chain
reconstruction (105°W)

Figure 4. A three-dimensional image of the ionosphere obtained from multiple CIT chains.

not know whether the ionosphere is affected more by the magnetosphere impinging on it or by the upper atmosphere impinging from below because of the lack of ionospheric measurements over a large spatially extended region and over many days. CIT provides this kind of measurement and can be used to probe the underlying physics of magnetic storm effects on the ionosphere.

Traveling ionospheric disturbances are known to be large-scale waves (periods from ≈30 min through several hours, wavelengths from ≈100 to 1000 km) that originate in the upper atmosphere and propagate into the ionosphere. CIT is well suited to study these phenomena, since it provides large spatial information from which we can gain data about the wavelength and vertical distribution of these waves.

Ionospheric variability refers to daily variations in the ionosphere. Such a day-to-day picture is important, both in terms of understanding the limitations of models and improving them. Most models, however, are climatological in nature and only predict monthly averages. With the CIT technique, 12 to 15 measurements per day over an extended spatial region are possible, thereby enabling long-term studies of the daily variation.

CIT receivers can sample the ionosphere at 50 Hz. This corresponds to a scale size of ≈80 m at the F region. The new receivers being developed should be able to sample at ≈1 kHz, corresponding to a scale size of ≈4 m. Ionospheric "turbulence," known to exist in the
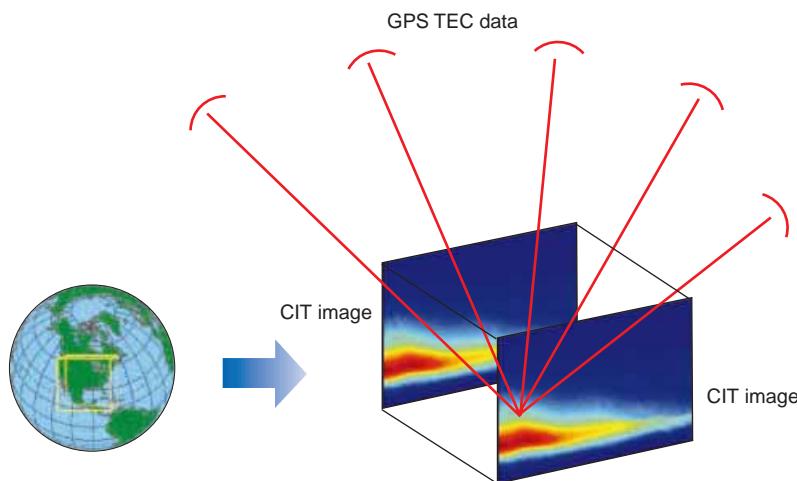

GPS TEC data

CIT image

CIT image

Figure 5. Representation of four-dimensional (three-dimensional plus time) CIT solution for ionospheric imaging. The Global Positioning System (GPS) measurements of total electron content (TEC) are used where Transit passes are not available.

auroral and equatorial regions of the Earth, produces scintillation on radio signals and can severely disrupt communications. A single Transit receiver sampling at the cited rates provides a snapshot of the latitudinal statistical properties of the turbulence. Two or more receivers separated by large ground paths can be used to correlate statistical properties and localize the turbulent region in space. Several phase-coherent receivers grouped together over ≈ 1 km^2 can be used to "invert" the data to produce a two-dimensional "picture" of the turbulence.

In addition to collecting Doppler data, CIT receivers collect the relative signal strength of the data. Although it has not been tried, there is no reason in principle that the signal strength cannot be used in tomography to invert a two-dimensional image of ionospheric absorption. This would be beneficial for all kinds of radio-frequency applications.

The true value of the CIT technique is its capability to provide real-time corrections to model parameters. The simplest method of doing so is correcting the coefficients for empirical models such as International Reference Ionosphere (IRI) 90 or the Parameterized Ionosphere Model (PIM). The more rigorous treatment is to use the data to adjust the initial and boundary conditions to a true first-principles physics model.

SUMMARY

The Transit system has been used for ionospheric research throughout its life. With the development of CIT technologies, the satellite portion of Transit continues to serve as an instructional tool for a more complete understanding of the processes that exist in the ionosphere. The near–real-time images obtained with CIT will enable more accurate calibration of operational systems (e.g., over-the-horizon radar and navigation systems) and improve the prediction of radio wave propagation effects. Several scientific areas have been identified that will extend the CIT concept in the future.[9,10]

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THE AUTHOR

ARNOLD J. TUCKER earned a Ph.D. in electrical engineering from The University of Texas at Austin in 1967. He began working at the university's Applied Research Laboratories (ARL) as a graduate student and eventually went on to become its Associate Director for Research. He has recently retired. During his tenure, Dr. Tucker had management oversight of three technical groups: information and technology, signal physics, and space and geophysics. He gained over 30 years of experience in satellite research and geodesy; ionospheric propagation measurements; passive radio-frequency emitter detection and position determination; tactical message collection, reduction, and analysis/radio-frequency mission planning systems; and system engineering and analysis.