SatTrack (V4.0) —
A Real-time Satellite Tracking
and Orbit Prediction Program

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Abstract —SatTrack (V4.0) is a stand-alone satellite orbit prediction and real-time tracking program for UNIX platforms with X Window System color graphics displays. Written in C language, the program displays the location of Earth satellites and provides information for ground station control. A batch mode allows predictions of satellite passes over specified ground stations. SatTrack features the SGP4 and SDP4 orbit propagation algorithms.

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1. INTRODUCTION

With about 7000 catalogued man-made objects orbiting around the Earth the demand for precision tracking is constantly growing [1]. Approximately 400 of those trackable objects are operational satellites. Tracking all of these objects serves a number of purposes: 1. Surveillance to keep the catalog of objects complete and up to date; 2. Communications between operational spacecraft and ground stations; 3. Imaging of objects from the ground at visible and infrared wavelengths. Tasks involved in tracking artifical Earth satellites, both operational and space debris, include predictions of satellite motions as well as real-time tracking applications for either monitoring satellite constellations, or to keep electronic or optical sensors precisely pointed at objects passing over a particular ground station.

Software needed to perform these tasks is usually rather complex. SatTrack (V4.0) is a newly

developed stand-alone program that performs both orbit prediction and simultaneous real-time tracking of a large number of artificial Earth satellites. The program is described below. It has been written in the C programming language and runs on a wide variety of UNIX platforms. Color graphics displays are based on X Window System (Version 11) library functions.

Keplerian Element Sets

Any tracking and orbit prediction program for Earth orbiting satellites relies on the detailed knowledge of the orbit geometry in order to precisely determine the state vector, i.e. the position and velocity in Earth Centered Inertial (ECI) Cartesian coordinates, of a specified object at a given instant of time. The accuracy of predicted satellite positions depends on many factors: the precision of initial conditions derived from observations, the accuracy of the adopted force model, the accuracy of the theory used in the calculations, and the time interval between the epoch of the initial state vector and the time of prediction [2].

The information on the orbit geometry is typically provided by the United States Space Command (USSPACECOM), formerly the North American Aerospace Defense Command (NORAD), and the National Aeronautics and Space Administration (NASA) in form of Two Line Keplerian Element (TLE) sets [3]. A TLE set for a given satellite basically contains the name and NORAD catalog number of the satellite; the inclination of the orbital plane, right ascension of the ascending node, and argument of perigee describing the orientation of the Kepler ellipse in space; the mean anomaly describing the location of the satellite on the ellipse at a specified time, known as the epoch; the mean motion and eccentricity, describing the size and shape of the orbit; several drag coefficients and first and second time derivatives of the mean motion, as well as the number of the reference orbit.

Orbit Propagation Models

TLE sets are generated based on certain models that take into account perturbations of satellite orbits caused by solar and lunar third-body effects, non-sphericity of the Earth's gravitational potential and atmospheric drag. Therefore, these very same models must also be used to predict the state vectors from these TLE sets for a given instant of time. Two different models, the Simplified General Perturbations Version 4 (SGP4) [3,4] and the Simplified Deepspace Perturbations Version 4 (SDP4) [3,5] orbit propagation algorithms, are being used for low-earth orbit satellites and for deep-space objects, i.e. those with an orbital period longer than 225 minutes, respectively. SatTrack uses these analytical models to calculate so-called osculating or instantaneous Kepler orbits as a function of time [6]. From these osculating orbits the actual state vector is obtained and then transformed into the Earth Centered Earth Fixed (ECEF) frame using standard astronomical coordinate transformations [7,8]. The resulting vector is subsequently transformed into observer centered coordinates using the current international geodetic reference system and the GRS 80 ellipsoid model of the Earth [9].

SatTrack Resource Files

SatTrack directly reads the TLE sets as its main input data. Several UNIX C shell scripts are provided to automatically retrieve current TLE data sets from various computers at the Air Force Institute of Technology (AFIT), NASA's Marshall Space Flight Center (MSFC) and Jet Propulsion Laboratory (JPL), using the Internet File Transfer Protocol (FTP). The SatTrack software package also contains several filter programs allowing users to concatenate TLE sets and create subsets for chosen groups of satellites.

Other resource files contain information on various SatTrack default start-up parameters and specific information for individual satellites, like alias names, launch dates, attitudes in orbit plane coordinates, uplink and downlink frequencies, transmission modes, and the data base with the ground station locations.

Depending upon the specific needs of particular applications, SatTrack (V4.0) can be configured in four different ways:

A. Basic orbit propagation and pass prediction in tabular form

B. Real-time tracking with text and numerical live displays

C. World map and sky view displays with X11 color graphics

D. Graphical user interface (GUI) for interactive program control in the real-time tracking mode

Configuration A is the basic configuration, and D the most sophisticated one, comprising all features of the lower configuration levels A–C. These features will be described in more detail in the next four sections.

2. ORBIT PREDICTION MODE

In the orbit prediction mode SatTrack calculates the circumstances of satellite passes for a specified ground station. The data will be either displayed on the video terminal or written into a file that can later be obtained as a hardcopy. The program generates tables in a short and in a long format. The orbit prediction can be run either interactively or in a batch mode. In the latter case all necessary parameters are specified on the command line.

Short Prediction Format

The prediction of passes in the short form list-ing gives the circumstances, i.e. the timing, geometry and visibility conditions, for every pass during a specified time interval. The prediction table contains one line per pass, indicating the time at Acquisition of Signal (AOS), Maximum Elevation (MEL) and Loss of Signal (LOS), the duration of the pass, the azimuth at AOS, MEL and LOS, the maximum elevation of the pass, a 5-digit visibility code, and the object's orbit number at the moment of AOS. Also, if a launch date is specified, an additional column shows the Mission Elapsed Time (MET) at AOS. A number of filter functions allows the user to list only passes with a certain minimum elevation and spacecraft lighting conditions.

Long Prediction Format

The prediction in the long format consists of a number of columns. The first column is the time in specified fixed increments from line to line. Other columns are the azimuth and elevation angles, range, latitude and longitude of the sub-satellite point, the satellite's orbital height, apparent right ascension and declination, the angle between the Sun, the satellite and the observer, the Doppler shift and free-space path loss, satellite lighting conditions and more. Depending upon the needs of a particular application, these columns can be configured by the operator in a number of different ways.

3. REAL–TIME TRACKING

SatTrack (V4.0) provides two different numerical live displays, for single or multiple satellites. Cursor controls used in both live displays are compatible with the VT100 standard, allowing the program to be run basically from any terminal.

SatTrack can track a single satellite and/or display multiple satellites for a primary ground station. An autotrack mode allows switching between any number of specified satellites as

they rise and set. A fast-forward mode allows stepping through the satellite motions at specified rates. Tracking of the Sun and the Moon are also provided for pointing tests and receiver calibration purposes.

The SatTrack source code allows direct control of antennas, optical telescopes, sensors, and radio communications equipment with proper Doppler corrections for telemetry, data or message forwarding applications. Additional user specific modules can be implemented with ease. The tracking calculations can be performed ahead of time, if required, to allow dedicated sensor control computers to react timely. Generally, SatTrack can send the tracking control information, i.e. character strings containing the current time, azimuth and elevation angles, Doppler-corrected uplink and downlink frequencies and other critical parameters, to any interface (serial or parallel ports, files, sockets, pipes) as often as once per second.

The location of the ground station can be either fixed or mobile. The latter case can be useful for land and maritime mobile, or even airborne applications. In this case current latitude, longitude and altitude, or the Maidenhead grid locator [10] can be read from a Global Positioning System (GPS) receiver.

Multiple Satellite Display

The multiple satellite live display shows one line per satellite with its rise and set times, visibility conditions during the upcoming pass, current azimuth and elevation angles, range and location of the sub-satellite point. Satellites are shown in the order of the time of AOS if they are below the horizon, or in reverse order of the time of LOS if they are above the horizon. This display also has a mode in which it shows the inter-satellite range between a selected object and any other object in the list of currently tracked objects. Also, for any selected object

the inter-satellite visibility is displayed between that object and the Tracking and Data Relay Satellite (TDRS) System (TDRSS) [11].

The number of satellites in the multiple satellite display is limited only by the speed and memory size of the computer SatTrack runs on. If more satellites are tracked than there are number of lines on the display, the user can page up or down to monitor all satellites being tracked. Other commands allow objects to be added or deleted from the autotrack list. Any object can be marked as the selected one. The user can then switch back and forth between the multiple satellite and the single satellite display for the selected satellite. Examples of the screen layout for both numerical real-time displays are shown below, as they are also part of the graphical user interface.

Single Satellite Display

The single satellite display shows more detailed current orbital information for the selected satellite and the primary ground station. These data comprise current azimuth and elevation angles, range and range rate, latitude and longitude of the sub-satellite point, orbital height and velocity, the instantaneous state vector, several event timers, the circumstances of the next pass, distance and direction of the sub-satellite point with respect to the nearest ground station, information for radio frequency communication like Doppler corrected uplink and downlink frequencies, and the uplink and downlink free-space path loss. Also shown are the angular position of the Sun and the Moon, as seen from the primary ground station.

4. GRAPHICS WINDOWS

When SatTrack is run from an X Window console the real-time graphics displays can be started up. SatTrack (V4.0) generates two different color graphics displays: a world map

tracking chart and a radar-type view of the local sky.

World Map Tracking Chart

The SatTrack distribution contains eight different world maps, all 360 by 180 deg in cylindrical projection. There are two different styles, the *fill style* and the *line style,* with four sizes each. The user can choose any of those depending upon available computing bandwidth, size of the graphics screen and personal taste. In addition, the user has a choice of six different color schemes. Amongst these color schemes are the blue and green style, known from the NASA Distributed Earth Model and Orbiter System (DEMOS) real-time display, the dark and light blue style, known from the big screen in NASA's mission control center, a red-only style for darkroom environments, and a black-and-white style for high-contrast hardcopies of the graphics windows.

Examples of the world map tracking chart are shown in Figs. 1 & 2. SatTrack will show the location of any number of specified satellites superimposed on the world map. Special icons are provided for the Space Shuttle, the Russian Space Station Mir and the International Space Station (ISS). The satellite icons or markers indicate if a particular satellite is in daylight or darkness. The satellite's name or its object number is displayed next to the icon or marker. The text in the header and footer lines refers to the selected satellite and the primary ground station.

The circle of visibility of a satellite, also referred to as its *footprint,* is featured for any spacecraft marked in the multiple satellite display. Correspondingly, the acquisition circle is displayed for the primary and any number of secondary ground stations. Also shown are the ground track of the selected satellite for the next three orbits and the inter-satellite visibility between this satellite and the TDRS satellites. The oblong feature over the Indian Ocean (cf. Figs. 1 & 2), known as the Zone of Exclusion (ZOE), shows where no communication through either TDRS satellite (in this case TDRS 3 and TDRS 4) is possible. Other display features include the Sun and the terminator with the dark side of the Earth shaded in, the ground station nearest to the sub-satellite point, and the MET. Grid lines are spaced by 30 deg in latitude and longitude.

Sky View Display

A second graphics display shows a radar-type view of the local sky with the predicted track of the selected satellite. This display contains all of the satellites currently being tracked that are above the horizon at the location of the primary ground station. Two examples of the sky view display are presented in Figs. 3 & 4. Elevation circles are spaced by 10 deg. The outermost circle is the horizon, and the center cross corresponds to the zenith. North is up, and East to the left, as indicated in the display. The object markers indicate the direction of travel and the lighting conditions with different colors for the daytime and nighttime part of the orbit.

The content of both graphics windows can be written to a file in the X Window Dump (XWD) format.

5. GRAPHICAL USER INTERFACE

The new GUI allows controlling all SatTrack program functions in a user friendly form. The central part of the window shows the numerical tracking data in either the multiple satellite mode (Fig. 5) or the single satellite mode (Fig. 6). Mouse activated buttons in the two rows below the central window are used to control display features in the graphics displays and the real-time tracking functions. Four of these buttons are programmed to reload or update data from a number of resource files. The column
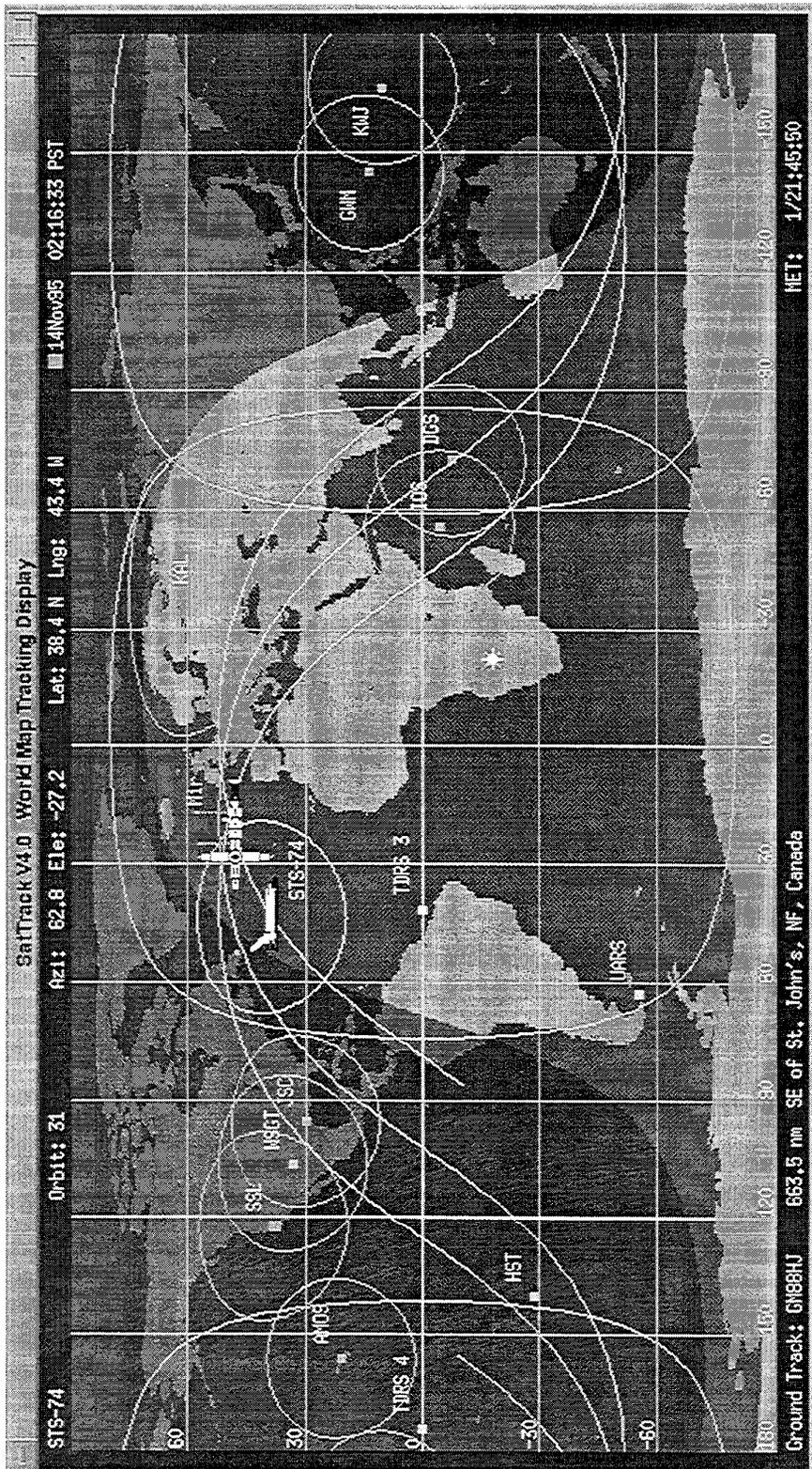
Figure 1. World map tracking chart in cylindrical projection, showing the features discussed in the text.
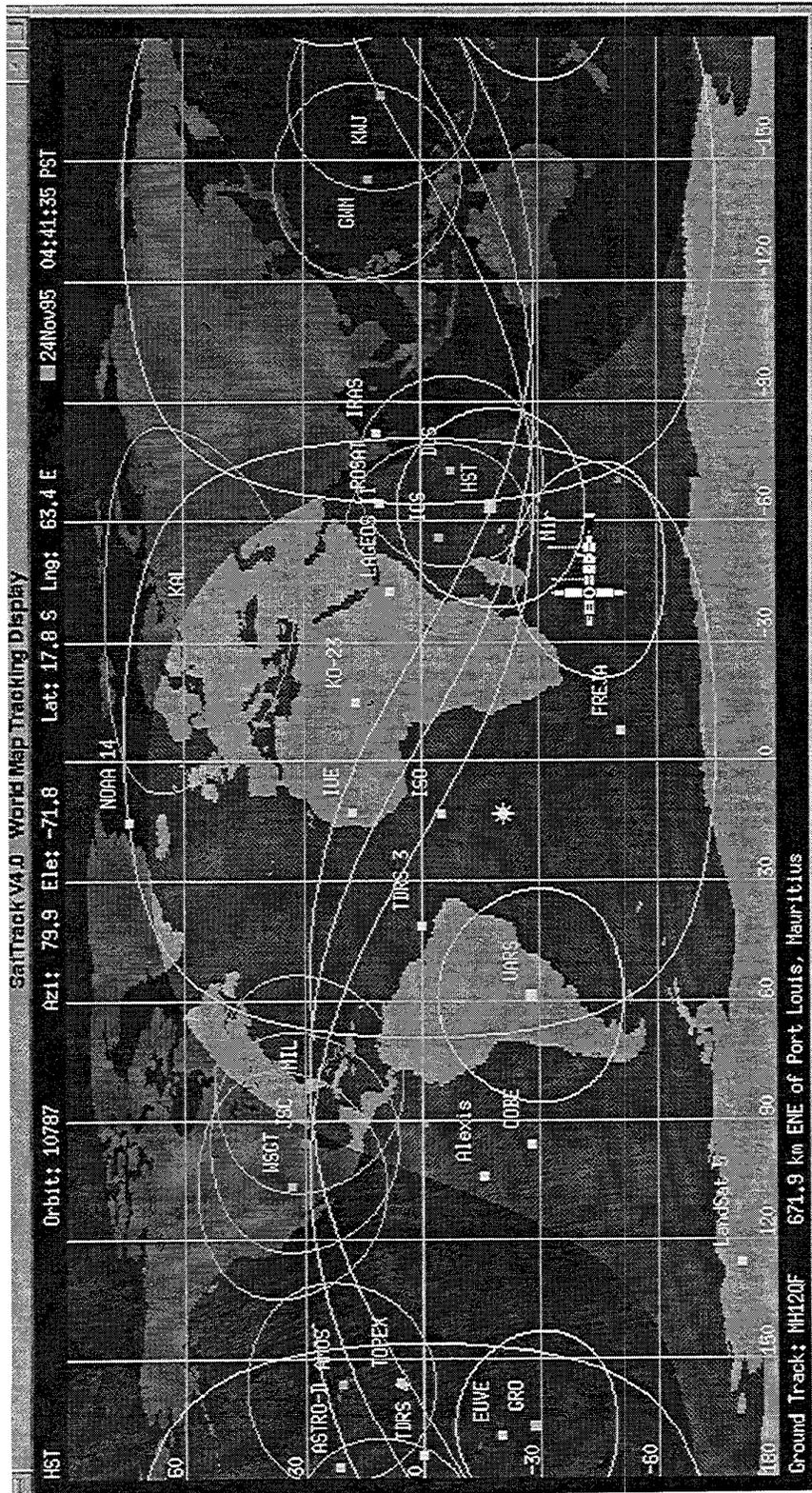
Figure 2. Another example of the world map tracking chart with a larger number of satellites.

of buttons to the right of the central window is used to manipulate the multiple satellite list. A message window below the title frame notifies the user of certain events or warnings.

In the multiple satellite mode, shown in Fig. 5, the individual lines are color coded to indicate if a particular satellite is currently marked for auto-tracking, and if the satellite is above the local horizon. The multiple satellite display is organized as discussed earlier in Section 3. An example for the real-time display in the single satellite mode is shown in Fig. 6.

The SatTrack (V4.0) graphical user interface has been developed around a special new set of on-screen building blocks, such as push buttons with callback functions and dialog boxes. These *widgets* do not depend upon commonly used Open Software Foundation (OSF) Motif libraries [12]. This approach makes SatTrack completely independent of other commercial software packages, except those libraries that are part of the UNIX operating system and the X Window System.

6. ACCURACY OF ORBIT PROPAGATION

A number of tests have been made to verify the functionality of the software and to determine the accuracy of the orbit propagation algorithms under a variety of conditions.

Model Implementation Test

Using the built-in state vector test feature, the results of the calculations of the SatTrack (V4.0) SGP4 and SDP4 state vectors were compared with the numerical examples tabulated in [3]. After a propagation time of one day the agreement in the X, Y and Z ECI coordinates was found to be 3.0 m (1 σ) for the SGP4 model and 2.7 m (1 σ) for the SDP4 model. The velocities agree in all three axes after one day within 0.004 m/s (1 σ) for the SGP4 model, and within 0.0006 m/s (1 σ) for the SDP4 model. This test demonstrates that the SatTrack implementation of these models reproduces the quoted examples with the expected numerical precision.

Comparison with Other Software

The precision of SatTrack's real-time tracking display was also checked against real-time tracking charts generated with DEMOS. It was shown that SatTrack (V4.0) and DEMOS are in excellent agreement.

The Low Precision Model

For applications that require lower precision, a simpler propagation model is provided, here called the *TLE Mean Model*. This model does not take into account any perturbations of the satellite's orbits and uses simplified drag terms for the mean motion. The bearings of a number of GPS satellites as calculated by SatTrack (V4.0) using this model were compared with those displayed on a GPS receiver, and they all agreed well within less than one deg in azimuth and elevation angles. The results of the TLE Mean Model were also compared with those from the SGP4 and SDP4 models. With two-day old TLE sets, the agreement between satellite positions calculated from the TLE Mean Model and the SGP4 model is 10 km (1 σ), and 20 km (1 σ) between the TLE Mean Model and the SDP4 model.

Intrinsic Accuracy of the TLE Sets

The TLE data sets are updated by USSPACE-COM or by the Flight Dynamics Division (FDD) at NASA's Goddard Space Flight Center (GSFC) when predicted and observed position of a given satellite differ by more than a preset tolerance limit. For publicly available TLE data sets this limit is of the order of 5 km for a particular satellite, mainly in the direction of travel along the orbit. This means that for objects in low-
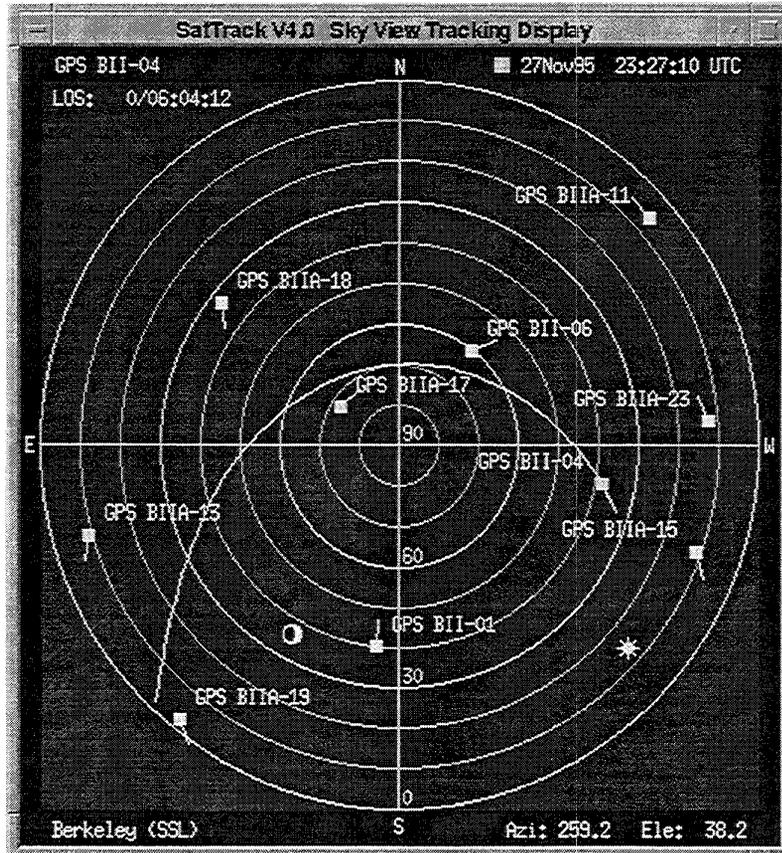
Figure 3. Example of the sky view display with all GPS satellites currently above the horizon at Berkeley. Elevation circles are spaced by 10 deg. The outermost circle is the horizon, and the center cross corresponds to the zenith. The object markers indicate direction of travel and lighting conditions. The track across the sky is shown for a selected satellite, here GPS BII-04 (SVN 19, PRN 19), and indicates whether that satellite is in sunlight or in the Earth's shadow.

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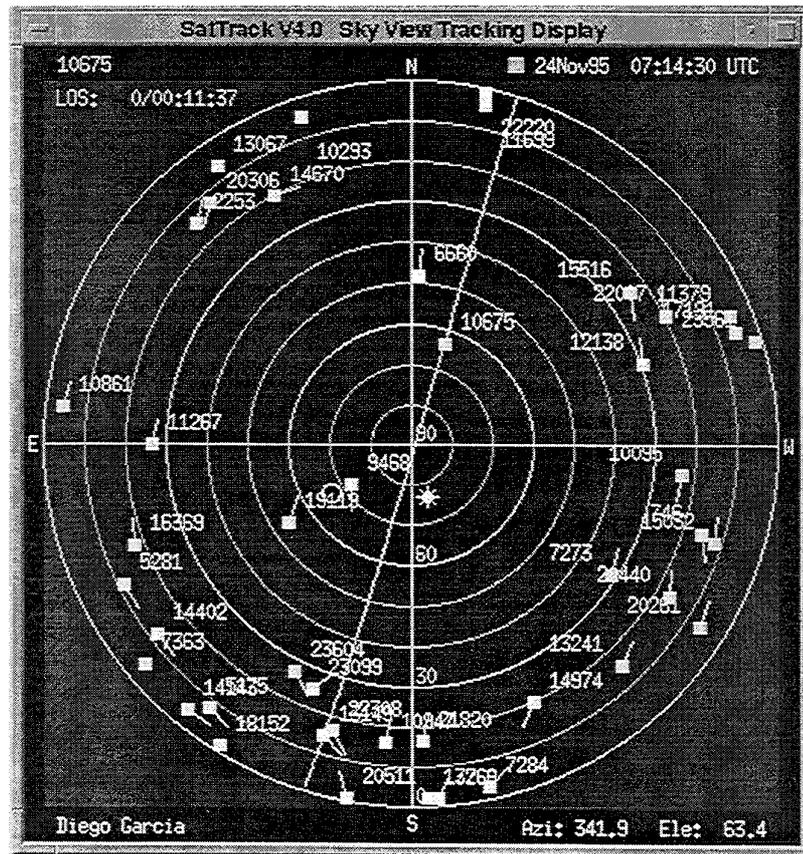
Figure 4. Another example of the sky view display shows a large number of satellites above the local horizon at the Diego Garcia tracking station in the Indian Ocean. The track across the sky is shown for the selected object 10675.

earth orbit the deviation between observed and predicted azimuth and elevation angles as seen from the location of the observer can be as large as 1.4 deg, or 0.7 s in time.

Several typical examples for the update time interval of the TLE sets are given for five different satellites: 3.4 days for IUE; 1.7 days for TDRS 4; 3.2 days for HST; 0.7 days for NOAA 12; as short as 2 hours for missions with frequent orbit correction maneuvers (STS–74 Atlantis/Mir docking mission). These update time intervals have been obtained by analyzing daily issued TLE sets for these objects over a period of 40 days. Users who are interested in high precision need to obtain updated TLE sets as frequently as possible.

7. TRACKING EXPERIMENTS

The real-time tracking capabilities of SatTrack have been demonstrated by observing satellites with the two 65-inch trailer-mounted telescopes of the Infrared Spatial Interferometer (ISI) [13]. This telescope system has its own control computers (Motorola MVME-147S) running the VxWorks real-time operating system (Wind River Systems, Inc.). SatTrack runs on a UNIX host computer (Sun SPARCstation IPC) and is interfaced to the Motorola VMEbus computers via Remote Procedure Calls (RPC). The tracking information is sent over the Ethernet once every second and ten seconds ahead of time. The real-time control computers then interpolate the tracking data 100 times per second in order to perform smooth tracking of the target object.

The drawbacks of this telescope system with respect to observations of artificial Earth satellites arise from the fact that it has been designed for observations of objects that move across the sky at the sidereal rate. The tracking rate of the telescopes is limited to about 1 deg/s. The particular Pfund-type geometry of the telescope

optics allows access to only half of the visible sky. Also, the Field of View (FOV) is optimized for high-resolution observations of stars and is limited to 53 seconds of arc. The presently used visible light guider cameras have a sensitivity limit of 12-14 mag, which basically precludes observations of geostationary objects.

Experimental Results

Despite these less than ideal experimental conditions it was tried to acquire low-earth orbit satellites with one of the ISI telescopes. About a dozen preliminary tracking tests have been performed during terminator passes with the Compton Gamma Ray Observatory (GRO), the Hubble Space Telescope (HST), and Space Shuttle Atlantis docked to the Mir Space Station on mission STS–74. In all cases the image of the tracked object was initially found in the focal plane of the telescope within 5 minutes of arc of the optical axis. In two cases the image of HST showed up in the FOV of the autoguider camera. It has to be mentioned that the acquisition tests were performed during the rising part of each pass when the object's velocity vector had a strong radial component (70% or larger) towards the ground station which reduced the effects of in-track position errors. The two-line Keplerian element sets used for these tests were not more than a few days old.

8. SYSTEM REQUIREMENTS

SatTrack (V4.0) can be installed on UNIX systems either as a single-user program or in a multi-user configuration with optional private resource files for each user.

Since all of SatTrack's graphics applications are based on X11 and X11 Toolkit functions only [12], the C language source code was easily ported to a wide variety of UNIX and Linux platforms: Sun SPARCstation IPC, 4, 5 or 10 with SunOS 4.1.x or Solaris 2.x; HP Apollo

SatTrack V4.0 Realtime Tracking Display

SatTrack V4.0
Licensed to tbt

Station: Merritt Island (MIL)
Satellite: STS-74 (Atlantis)

Date: Tue 14Nov95
UTC: 318 11:41:03

Updated TLE sets

Satellite	Countdown	Next AOS/LOS	Duration	MEL	Visib		Azi	Ele	Range		Ground Track Location
TDRS 3	Geostationary satellite					D	120	36\	38111	442 km	NE Alcantara (ALC), Brazil
UE	2/20:07:42	321/07:48:46	72:00:52	48*	VWWV	D	72	24\	36664	211 km	NE Las Palmas, Canary Islands (Spain)
IRAS	0/00:10:53	318/11:51:56	0:15:34	37	DDDDD	D	209	21/	1870	168 km	SSE Belize City, Belize
STS-74	0/00:08:31	318/11:49:34	0:10:05	71*	DDDDD	D	217	15\	1511	72 km	NW Belize City, Belize
Mir	0/00:04:19	318/11:45:23	0:10:28	62*	DDDDD	D	68	39\	595	423 km	ENE Cape Canaveral AFS, FL, USA
ASTRO-D	0/00:10:49	318/11:51:53	0:11:03	17	DDDDD	N	291	-25/	6617	1255 km	NNE Hana, Maui, HI, USA
COBE	0/01:02:12	318/12:43:16	0:15:39	43*	DDDDD	D	189	-53\	11260	1148 km	SW Siple Station, Antarctica (USA)
Alexis	0/01:03:16	318/12:44:19	0:10:32	8	DDDDD	N	348	-54\	11345	154 km	ESE Wuzhai (WUZ), China
LandSat 5	0/01:25:54	318/13:06:58	0:07:14	4	DDDDD	D	126	-22\	6210	394 km	W Recife, Brazil
LAGEOS II	0/01:57:07	318/13:38:11	1:19:47	54*	DDDDD	D	39	-58\	17301	793 km	NNW Male, Maldives
HST	0/02:17:34	318/13:58:38	0:09:54	9	DDDDD	N	271	-64/	12153	580 km	E Cairns, Australia
FREJA	0/02:21:01	318/14:02:05	0:14:57	7	DDDDD	N	255	-46/	9948	295 km	SE Pago Pago, American Samoa (USA)
ROSAT	0/03:10:07	318/14:51:11	0:11:04	17	DDDDD	D	105	-20\	5655	1244 km	SW Praia, Cape Verde Islands (Spain)
EUVE	0/04:49:45	318/16:30:49	0:10:29	14	DDDDD	N	119	-20\	5662	231 km	N Fortaleza, Brasil
NOAA 14	0/05:54:28	318/17:35:32	0:13:32	19	DDDDD	N	244	-38\	9098	310 km	SW Papeete, Tahiti (France)
UARS	0/07:05:13	318/18:46:17	0:10:54	14	DDDDD	N	226	-35\	8230	517 km	SW Pitcairn Island (UK)
KO-23	0/07:38:01	318/19:19:05	0:15:26	11	DDDDD	D	109	-61\	12592	855 km	S Inhambane, Mozambique
GRO	0/08:42:00	318/20:23:04	0:09:42	14	DDDDD	N	277	-42/	9218	859 km	NNE Baker Island (USA)
TOPEX	0/09:34:29	318/21:15:33	0:19:42	27	DDDDD	N	120	-67\	13167	626 km	NNW Crozet Islands (France)
TDRS 4	Geostationary satellite					D	272	-12/	43010	220 km	E Baker Island (USA)

Demo
Single Sat
Objects
Next Set
Next Rise
Find
Select
Add / Del
Page Up
Page Down
Start
Quit

World Map | Sky View | Fast Mode | Tracking | Autotrack | Frequency | Update TLE | Update Loc
Horizon | Foot Print | TDRS 20E | All Cities | Stations | Tune | Reload Def | Add Station

Figure 5. Graphical user interface (GUI) for real-time tracking control in the multiple satellite mode.

SatTrack V4.0 Realtime Tracking Display

Station: Mt. Wilson (MWO)
Satellite: STS-74 (Atlantis)

Date: Tue 14Nov95
UTC: 318 14:49:33

SatTrack V4.0
Licensed to KST

Updated TLE sets

bts

Demo

Multi Sat
Objects
Next Set
Next Rise
Find
Select
Add / Del
Page Up
Page Down

Start
Quit

Update TLE   Frequency   Autotrack   Tracking   Fast Mode   Sky View   World Map
Update Log
Add Station   Reload Def   Tune   Stations   All Cities   TDRSS ZOE   Foot Print   Horizon

SatTrack V4.0   STS-74 TRACKING DISPLAY   BTS

Ground Stn :Mt. Wilson (MWO)   Date: Tue 14Nov95   DownLink AM : 259.7051 MHz
Shuttle   : Atlantis   UTC : 318 14:49:33   UpLink NONE: 0.0000 MHz
Inclination: 51.644 deg   DownLink Loss: 137.4300 dB
Orbit   : 34 11.3 % D   Object   :   23714   UpLink Loss: 0.0000 dB
Sun Az/El: 115.2   4.2 deg   TLE Set :   7   Sun Angle :   67.1890 deg
Moon Az/El: 231.5 58.4 deg   Tracking: ON   Phase (256): 66.4200 AM

Azimuth   :   234.767 deg   Latitude :   31.225 deg N /
Elevation :   30.534 deg /   Longitude : 122.830 deg W
Range   :   383.077 nm   Height   : 195.851 nm
Range Rate: -3.209 nm/s   Velocity :   4.152 nm/s

State Vector X: -2774.308 nm   Y: +1427.800 nm   Z: +1879.501 nm /
              VX: -0.072 nm/s VY: -3.346 nm/s   VZ: +2.457 nm/s

Last AOS : 318/14:45:46 UTC   AOS Azimuth : 228.500 deg DD
Duration : 0/00:10:10   MEL Azimuth : 303.900 deg D
Next LOS : 318/14:55:56 UTC   LOS Azimuth :   46.100 deg BB
Countdown : 0/00:06:23   Max Elevation: 77.700 deg
MET   : 2/02:18:50   MEL Range   : 206.600 nm

Ground Track: CN810F   239.8 nm SSW of Vandenberg AFB (VAN), CA, USA
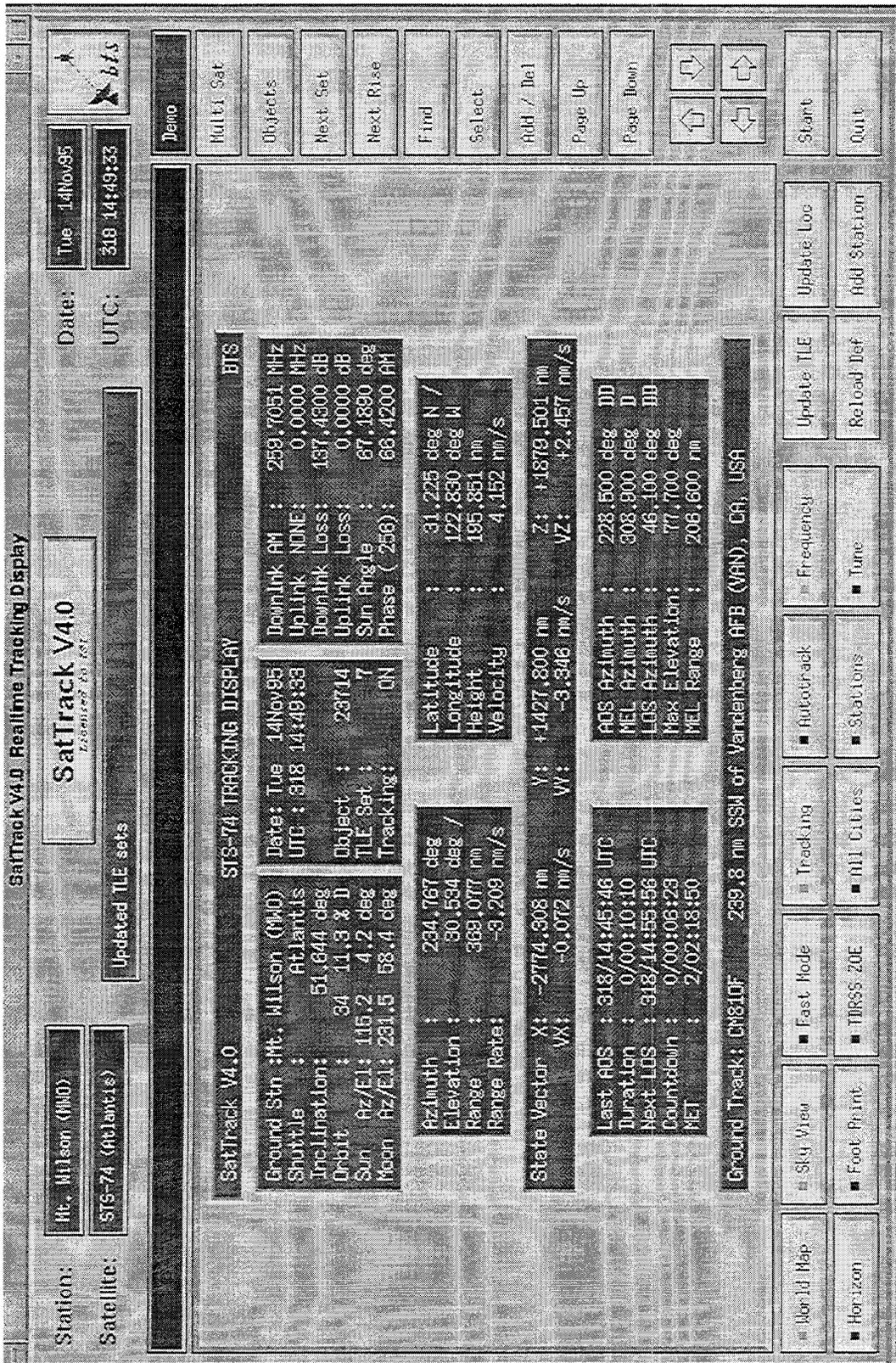
Figure 6. Graphical user interface (GUI) for real-time tracking control in the single satellite mode.

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9000 Series 700 with HPUX; IBM RS–6000 with AIX; DEC Alpha with AXP/OSF; SGI Indigo 2 with IRIX 5.3; i386 and x386 with Linux, NetBSD, FreeBSD and BSDI; X11R4, X11R5 and X11R6 with various window managers.

The SatTrack (V4.0) installation requires approximately 10 MB of disk space. In the single satellite mode, an i386 or 68030-type CPU with a math co-processor is adequate. For running the program in the multiple satellite mode with 20 satellites and with the color graphics displays, a machine of i486 or even SPARCstation quality is recommended. When SatTrack is run in the multiple satellite mode with 1500 low-earth orbit and deep-space objects, a Sun SPARCstation 4 can update the real-time numerical display once every 15 seconds. SatTrack (V4.0) requires about 6 MB of memory at run time when tracking 1500 objects with all graphics windows open.

9. APPLICATIONS

Applications of this software package range from visualizing orbits or monitoring positions of individual artificial Earth satellites, or any groups of satellites like the GPS, to prediction of GPS Dilution of Precision (DOP) 'holes', Space Shuttle mission planning and mission control objectives. Since SatTrack displays inter-satellite ranges both in real-time and in a fast-forward mode, this program can be used to perform on-line collision avoidance analysis between manned spacecraft and other objects. Warning levels for a minimum separation can be configured by the operator.

The software package also allows automated ground station control, for example for downloading of weather images, telemetry and remote sensing data, or for message forwarding. A wide number of applications becomes feasible with the real-time hooks built into modern

UNIX systems like Solaris 2.3 (Sun Microsystems, Inc.), or in conjunction with VxWorks (Wind River Systems, Inc.).

10. CONCLUSIONS

The SatTrack (V4.0) software package has been shown to provide accurate orbit propagation of artificial Earth satellites. The source code has been written in modular form so that it can be easily modified, adapted and expanded to the needs of individual projects. More options like world maps in different projections, including zooming and 3D graphics, and plots (hardcopies in PostScript format) of satellite traces either on the world map or on the local sky, and predictions of inter-satellite visibilities and inter-satellite ranges as a function of time are in the planning stage and will be featured in a future version of SatTrack.

Users of earlier versions of SatTrack (V3.1) include JPL, GSFC, MSFC, the European Space Agency (ESA), the German Space Agency (DLR), the National Aerospace Laboratory (NLR) of The Netherlands, the Los Alamos National Laboratory (LANL), the Amundsen-Scott South Pole Station, and a large number of universities and other institutions.

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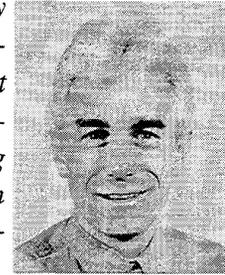
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